Tests of the standard electroweak model in beta decay[*†]

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We review the current status of precision measurements in allowed nuclear beta decay, including neutron decay, with emphasis on their potential to look for new physics beyond the standard electroweak model. The experimental results are interpreted in the framework of phenomenological model-independent descriptions of nuclear beta decay as well as in some specific extensions of the standard model. The values of the standard couplings and the constraints on the exotic couplings of the general beta decay Hamiltonian are updated. For the ratio between the axial and the vector couplings we obtain $C_A/C_V = -1.26992(69)$ under the standard model assumptions. Particular attention is devoted to the discussion of the sensitivity and complementarity of different precision experiments in direct beta decay. The prospects and the impact of recent developments of precision tools and of high intensity low energy beams are also addressed.

Contents

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I. INTRODUCTION

Nuclear beta decay has played a crucial role in the development of the weak interaction theory. Three experimental foundations of the standard electroweak model, *i.e.* *(i)* the assumption of maximal parity violation; *(ii)* the assumption of massless neutrinos; and *(iii)* the vector axial-vector character of the weak interaction have their sources in the detailed analysis of nuclear beta decay processes. The so-called *universal V-A* theory has been established from the analogy between nuclear beta decay and muon decay. The ensuing confrontation of the weak interaction theory, constructed at low energies, against the results obtained at higher energies, motivated the development of a gauge theory and constituted a significant step which led to the construction of the unified electroweak model.

The beta decay theory, including some of its refinements like the induced weak currents, has been firmly established and tested more than three decades ago and has later been embedded into the wider framework of the standard electroweak model. Since then the main motivations of new experiments performed at low energies, with ever increased statistical accuracy, have been to provide precision tests of the discrete symmetries as well as to address specific questions involving the light quarks, which are naturally best studied in nuclear and neutron decays.

Nuclear beta decay is a semi-leptonic strangeness-conserving process which, at the fundamental level and to lowest order, involves the lightest leptons (e,ν_e) and quarks (u,d) interacting via the exchange of the charged vector bosons $W_L^{\pm}$. The number of constraints on the standard model provided by these low energy experiments is actually limited as is also the number of relevant standard model parameters involved in the description of the semi-leptonic beta decay. In this sense the *tests of the standard model* considered at low energies generally refer to the tests of the underlying fundamental symmetries rather than to tests of the consistency of the theory or the predictions of new phenomena. The main aim of precision low energy experiments is to find deviations from the standard model assumptions as possible indications of new physics.

Despite the great success of the standard model, many open questions remain such as the hierarchy of fermion masses, the number of generations, the origin of parity violation, the mechanism behind CP violation, the number of parameters of the theory, etc. These are expected to find explanations in extended and unified theoretical frameworks involving new physics.

The production of intense sources and beams of β emitters (nuclei and neutrons), with high purity and possibly polarized, enables a high statistical accuracy to be reached in the determination of the parameters which describe the weak interaction in nuclei and in the searches for deviations from maximal parity violation or from time reversal invariance. In addition, the rich spectra of nuclear states and the combination with transitions involving other emitted particles (α, γ, p) following the beta decay transition, offer a large diversity to the design of low energy experiments and to implement different techniques. For well selected transitions the uncertainties associated with hadronic effects can be well controlled such that their impact remains below the experimental accuracy and does not affect the extraction of reliable results.

The role of beta decay experiments to test the standard model assumptions and to look for new physics has been discussed earlier in several papers (Deutsch and Quin, 1995; Herczeg, 1995a, 2001; van Klinken, 1996; Towner and Hardy, 1995; Yerozolimsky, 2000) with emphasis on specific aspects of this sector. We have heavily relied on these works to prepare the present review and we invite the reader to consult them for more details.

This review discusses nuclear beta decay within the framework of the standard model and beyond, with emphasis on the sensitivity of experiments looking for new physics. The article is organized as follows. The formalisms used for the beta decay interaction are presented in Sec. II, where several parameterizations are reviewed and the relations between them are discussed. The expressions of the correlation coefficients as a function of the relevant couplings, which are used and discussed in the following sections, are given in the appendix. Section III examines the present status of the standard theory in terms of the values of the weak couplings and the constraints derived from the most precise data available to date. In particular, selected results obtained over the past decade have been included. Several assumptions on the couplings are considered and the updated values and constraints are discussed. In Sec. IV the properties and correlation parameters accessible to beta decay experiments are reviewed. As a given correlation parameter provides information on several questions concerning the tests of the standard model while a given question can be addressed by considering different observables, a two-way approach is needed. The potential sensitivity to new physics and the current most precise results are presented for each measured quantity. The current experimental difficulties and future plans and developments are discussed. The conclusions on the present achievements and some future perspectives in the field are summarized in Sec. V.

Several fundamental questions addressed by other decay or capture experiments, like the test of lepton number violation and the determination of the nature of the neutrino in neutrino-less double beta decay experiments, are not covered in this article. The measurements which indicate that neutrinos are massive and oscillate and their consequences have been the subject of a number of dedicated reviews of this very important and rapidly changing field (Bemporad *et al.*, 2002; Jung *et al.*, 2001; Kajita and Totsuka, 2001). The status and prospects of double beta decay experiments

(Elliot and Vogel, 2002; Zdesenko, 2002) and muon decay experiments (Kuno and Okada, 2001) have also recently been reviewed.

II. FORMALISMS OF ALLOWED BETA-DECAY

The elaboration of the weak interaction theory has been retraced in many books and reviews. The most relevant original publications have been summarized and analyzed in different contexts (Bertin *et al.*, 1984; Kabir, 1963). Several classical texts (Konopinski, 1966; Schopper, 1966; Wu and Moszkowski, 1966) introduce the theory with appropriate references to the early experiments and provide also the basics of the phenomenological description of nuclear beta decay. More recent texts (Commins and Bucksbaum, 1983; Greiner and Müller, 1996; Holstein, 1989) place nuclear beta decay in the context of the unified electroweak theory.

The beta transitions are traditionally divided into *allowed* and *forbidden*. Allowed transitions correspond to processes in which no orbital angular momentum is carried away by the pair of leptons. Their selection rules are:

$$\Delta J = J_i - J_f = 0, \pm 1 \tag{1}$$

$$\pi_i \pi_f = +1 \tag{2}$$

where J_i and π_i (J_f and π_f) designate the spin and parity of the initial (final) state. The allowed transitions can then be subdivided into singlet and triplet components depending on whether the lepton spins are anti-parallel ($S = 0$) or parallel ($S = 1$). In allowed transitions the singlet state can only arise when $\Delta J = 0$ (Fermi selection rule) whereas the triplet state corresponds to $\Delta J = 0, \pm 1$ (Gamow-Teller selection rule). In this last case, transitions between states of zero angular momentum ($0 \to 0$) are excluded since it is impossible to generate a triplet state for $\mathbf{J}_i = \mathbf{J}_f = \mathbf{0}$.

A. The V-A Theory

The electroweak interaction is described by the standard model (Salam and Ward, 1964; Weinberg, 1967). The symmetries of the underlying $SU_L(2) \times U(1)$ gauge group determine the properties of the interaction and generate the intermediate vector bosons. Figure 1 shows a diagram of a β-decay process described at the elementary quark-lepton level by the exchange of a charged weak boson W^+.

In low-energy processes like β-decay, in which the typical energies involved in the process are much smaller than the mass of the weak bosons, the interaction can be described by a four-fermion contact interaction. Such formulation was first introduced with a vector interaction (Fermi, 1934), it was later extended (Gamow and Teller,

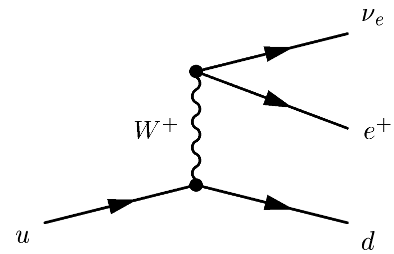

FIG. 1 The β-decay at the quark-lepton level, mediated by the exchange of a weak boson.

1936) to describe transitions which required the introduction of other possible Lorentz invariants and it was finally generalized (Feynman and Gell-Mann, 1958; Sudarshan and Marshak, 1958) as a universal formulation of the weak interaction, incorporating the assumption of maximal parity violation. The Hamiltonian of the *V-A theory* resulting from such a four-fermion contact interaction has the form of a current-current interaction

$$\mathcal{H}_{V-A} = \frac{G_F}{\sqrt{2}} J_\mu^\dagger \cdot J_\mu + \text{H.c.} \tag{3}$$

where $G_F/(\hbar c)^3 = 1.16639(1) \times 10^{-5}$ GeV^{-2} is the Fermi coupling and the current J_μ contains a hadronic and a leptonic contribution

$$J_\mu = J_\mu^{had} + J_\mu^{lep} \tag{4}$$

The fact that the Fermi coupling has the dimension of (mass)$^{-2}$ indicates that it cannot correspond to a fundamental interaction strength whose value should not depend on a specific system of units. If g designates the coupling strength between the weak boson and the fermions at each vertex of Fig. 1 then, in the limit of low momentum transfer, one has a simple relation between the Fermi coupling of the *V-A* theory and the boson mass, M_W,

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} \tag{5}$$

Figure 2 shows the same decay process as in Fig. 1 but in which the four fermions interact at a single point.

The β-decay of the neutron and of nuclei are described by a diagram similar to Fig. 2.

B. Quark mixing

The relative strength of the weak interaction in pure leptonic, in semi-leptonic and in pure hadronic processes are not identical. This has been incorporated into the electroweak theory by the mechanism of quark mixing. The weak eigenstates of the quarks with charge

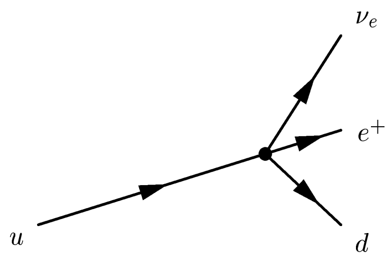

FIG. 2 Contact interaction of four fermions. The hadronic and leptonic currents interact at a single point.

$-1/3$ are postulated to differ from the eigenstates of the electromagnetic and strong interaction, which define the mass eigenstates. In the case of the three quark families the mixing is expressed by means of the Cabibbo-Kobayashi-Maskawa (CKM) matrix (Cabibbo, 1963; Kobayashi and Maskawa, 1972)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Here the primes denote the weak eigenstates. The normalization of the states requires the CKM-matrix to be unitary. For the u- and d-quarks involved in nuclear β-decay, in which the heavier quarks do not contribute to lowest order, we have

$$d' \simeq V_{ud} d = \cos\theta_C d \tag{6}$$

where θ_C is the Cabibbo angle. The weak interaction of the quark d' introduces then the matrix element V_{ud} in the amplitude of the hadronic current.

C. The general Hamiltonian

The most general interaction Hamiltonian density describing nuclear β-decay, including all possible interaction types consistent with Lorentz-invariance, is given by (Jackson, Treiman, and Wyld, 1957a; Lee and Yang, 1956)

$$\begin{aligned} \mathcal{H}_\beta \; = \; & (\bar{p}n)\,(\bar{e}\,(C_S + C_S'\gamma_5)\,\nu) \\ & + (\bar{p}\gamma_\mu n)\,(\bar{e}\gamma_\mu\,(C_V + C_V'\gamma_5)\,\nu) \\ & + \frac{1}{2}\,(\bar{p}\sigma_{\lambda\mu} n)\,(\bar{e}\sigma_{\lambda\mu}\,(C_T + C_T'\gamma_5)\,\nu) \\ & - (\bar{p}\gamma_\mu\gamma_5 n)\,(\bar{e}\gamma_\mu\gamma_5\,(C_A + C_A'\gamma_5)\,\nu) \\ & + (\bar{p}\gamma_5 n)\,(\bar{e}\gamma_5\,(C_P + C_P'\gamma_5)\,\nu) \\ & + \text{H.c.} \end{aligned} \tag{7}$$

with the tensor operator given by

$$\sigma_{\lambda\mu} \; = \; -\frac{i}{2}\,(\gamma_\lambda\gamma_\mu - \gamma_\mu\gamma_\lambda)\,. \tag{8}$$

The interacting fields are here associated to the nucleons and the leptons and the interactions are described by the five operators: the scalar $\mathcal{O}_S = 1$, the vector $\mathcal{O}_V = \gamma_\mu$, the tensor $\mathcal{O}_T = \sigma_{\lambda\mu}/\sqrt{2}$, the axial-vector $\mathcal{O}_A = -i\gamma_\mu\gamma_5$, and the pseudo-scalar $\mathcal{O}_P = \gamma_5$. The coefficients C_i and C_i' which appear in the leptonic currents determine the relative amplitude of each interaction. These amplitudes can be complex corresponding to a total of 20 real parameters[1] which determine the properties of the Hamiltonian with respect to space inversion (P), charge conjugation (C) and time reversal (T) symmetries.

The presence of both the C_i- and the C_i'-coefficients is related to the transformation properties under parity. Parity invariance holds for either $C_i' = 0$ or $C_i = 0$ and is violated if both C_i and C_i' are present. Maximum parity violation corresponds to $|C_i| = |C_i'|$. Charge-conjugation invariance holds if $Re(C_i/C_i') = 0$ or $Re(C_i'/C_i) = 0$, *i.e.* if the C_i are real and the C_i' are purely imaginary, up to an overall phase. When C_i and C_i' have both a real or both an imaginary part charge-conjugation is violated. Time-reversal invariance holds if the C_i and C_i' are all real up to an overall common phase and is violated if at least one of the couplings has an imaginary phase relative to the others. The relations between the C_i-coefficients and the symmetry properties of the interactions are summarized in Table I.

Symmetry	Condition for violation
C	($ReC_i \neq 0$ and $ReC_i' \neq 0$) or
	($ImC_i \neq 0$ and $ImC_i' \neq 0$)
P	$C_i \neq 0$ and $C_i' \neq 0$
T	$Im(C_i/C_j) \neq 0$ or $Im(C_i'/C_j) \neq 0$

TABLE I The consequences on the couplings due to the violations of the discrete symmetries.

In the non-relativistic treatment of the nucleons it is easy to show that the pseudo-scalar hadronic current, $\bar{p}\gamma_5 n$, vanishes and therefore the pseudo-scalar term in Eq. (7) can be neglected in calculations of the experimental observables. The scalar and vector interactions contribute to the Fermi (F) transitions whereas the axial and tensor interactions contribute to the Gamow-Teller (GT) transitions.

The description of β-decay in the minimal electroweak model involves only V- and A-interactions; parity is assumed to be maximally violated along with charge conjugation and the effects due to the standard CP (or T) violation observed in the K and B-meson systems are not

[1] One of these coefficients can be absorbed in the overall strength of the interaction provided it be the same for all β transitions. In the standard model and following CVC (see below) one fixes $C_V = G_F V_{ud}/\sqrt{2}$.

expected to contribute at the present level of experimental precision (Herczeg and Khriplovich, 1997). In terms of the couplings this leads to $C_V/C'_V = 1$, $C_A/C'_A = 1$, $C_S = C'_S = C_T = C'_T = C_P = C'_P = 0$, and $Im(C_i) = 0$ for all i.

In addition to the Lorentz invariants which are linear in the fermion fields the hadronic current can involve terms which depend on the field derivatives ("gradient" type contributions) associated with the hadronic structure. These are the so-called induced weak currents (Grenacs, 1985; Holstein, 1974, 1976; Mukhopadhyay, 1999) and are discussed in Sec. II.G. In Eq. (7) it is assumed that only one neutrino state is involved and that the effects due to a possibly finite neutrino mass are negligible.

D. Helicity projection formalism

Alternative formulations of the local four-fermion interaction, not including derivatives in the fermion fields, have been proposed to make more explicit the helicity structure of the interacting fermions (Herczeg, 1995a, 2001). In such formulations the most general interaction Hamiltonian, at the quark-lepton level, involving a left-handed neutrino state $\nu^{(L)}$ and a singlet right-handed neutrino state $\nu^{(R)}$, can be written as[2] (Herczeg, 2001)

$$H_\beta = H_{V,A} + H_{S,P} + H_T \tag{9}$$

where

$$\begin{aligned} H_{V,A} \;=\; & \bar{e}\gamma_\mu(1+\gamma_5)\nu^{(L)} \\ & [a_{LL}\bar{u}\gamma_\mu(1+\gamma_5)d + a_{LR}\bar{u}\gamma_\mu(1-\gamma_5)d] \\ & +\bar{e}\gamma_\mu(1-\gamma_5)\nu^{(R)} \\ & [a_{RR}\bar{u}\gamma_\mu(1-\gamma_5)d + a_{RL}\bar{u}\gamma_\mu(1+\gamma_5)d] \\ & +\text{H.c.} \end{aligned} \tag{10}$$

$$\begin{aligned} H_{S,P} \;=\; & \bar{e}(1+\gamma_5)\nu^{(L)} \\ & [A_{LL}\bar{u}(1+\gamma_5)d + A_{LR}\bar{u}(1-\gamma_5)d] \\ & +\bar{e}(1-\gamma_5)\nu^{(R)} \\ & [A_{RR}\bar{u}(1-\gamma_5)d + A_{RL}\bar{u}(1+\gamma_5)d] \\ & +\text{H.c.} \end{aligned} \tag{11}$$

$$\begin{aligned} H_T \;=\; & \alpha_{LL}\bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(1+\gamma_5)\nu^{(L)}\bar{u}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(1+\gamma_5)d \\ & +\alpha_{RR}\bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(1-\gamma_5)\nu^{(R)}\bar{u}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(1-\gamma_5)d \\ & +\text{H.c.} \end{aligned} \tag{12}$$

The terms in Eq. (10) have vector and axial-vector interactions, those given in Eq. (11) have scalar and pseudo-scalar interactions and Eq. (12) contains tensor interactions. The first subscript of the couplings a_{ij}, A_{ij} and α_{ij} gives the chirality of the neutrino and the second the chirality of the d-quark. The neutrino states $\nu^{(L)}$ and $\nu^{(R)}$ are in general linear combinations of the left-handed and right-handed components of the neutrino mass-eigenstates (Herczeg, 2001). In the standard model all couplings are zero except a_{LL} which becomes $(a_{LL})_{SM} = G_F V_{ud}/\sqrt{2}$.

The β-decay of the nucleon due to the interaction given in Eq. (9) is given by (Herczeg, 2001)

$$H_\beta^{(N)} \simeq H_{V,A}^{(N)} + H_S^{(N)} + H_T^{(N)} \tag{13}$$

where the pseudo-scalar contribution has been neglected and were the three terms are

$$\begin{aligned} H_{V,A}^{(N)} &= \bar{e}\gamma_\mu(C_V + C'_V\gamma_5)\nu\bar{p}\gamma_\mu n \\ &\quad -\bar{e}\gamma_\mu\gamma_5(C_A + C'_A\gamma_5)\nu\bar{p}\gamma_\mu\gamma_5 n + \text{H.c.} && (14) \\ H_{S,P}^{(N)} &= \bar{e}(C_S + C'_S\gamma_5)\nu\bar{p}n + \text{H.c.} && (15) \\ H_T^{(N)} &= \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T + C'_T\gamma_5)\nu\bar{p}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}n + \text{H.c.} && (16) \end{aligned}$$

The terms of the Hamiltonian in Eq. (13) are hence identical to those in Eq. (7). The relations between the couplings C_i and C'_i which appear in Eqs. (14-16) and those in Eqs. (10-12) are[3]

$$\begin{aligned} C_V &= g_V(a_{LL} + a_{LR} + a_{RR} + a_{RL}) && (17) \\ C'_V &= g_V(a_{LL} + a_{LR} - a_{RR} - a_{RL}) && (18) \\ C_A &= g_A(a_{LL} - a_{LR} + a_{RR} - a_{RL}) && (19) \\ C'_A &= g_A(a_{LL} - a_{LR} - a_{RR} + a_{RL}) && (20) \\ C_S &= g_S(A_{LL} + A_{LR} + A_{RR} + A_{RL}) && (21) \\ C'_S &= g_S(A_{LL} + A_{LR} - A_{RR} - A_{RL}) && (22) \\ C_T &= 2g_T(\alpha_{LL} + \alpha_{RR}) && (23) \\ C'_T &= 2g_T(\alpha_{LL} - \alpha_{RR}) && (24) \end{aligned}$$

The constants $g_i \equiv g_i(0)$, $i = V, A, S, T$, are the values of hadronic form factors in the limit of zero momentum transfer. They are defined by (Herczeg, 2001)

$$\begin{aligned} g_V(q^2)\bar{p}\gamma_\mu n &= \langle p|\bar{u}\gamma_\mu d|n\rangle && (25) \\ g_A(q^2)\bar{p}\gamma_\mu\gamma_5 n &= \langle p|\bar{u}\gamma_\mu\gamma_5 d|n\rangle && (26) \\ g_S(q^2)\bar{p}n &= \langle p|\bar{u}d|n\rangle && (27) \\ g_T(q^2)\bar{p}\sigma_{\lambda\mu} n &= \langle p|\bar{u}\sigma_{\lambda\mu} d|n\rangle && (28) \end{aligned}$$

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[2] See Appendix A for the conventions on the metric.

[3] Here the coefficients C_i and C'_i are the same as those in Eq. (7). The signs of C'_V, C_A, C'_S and C'_T are here opposite to those in Herczeg (2001).

In the standard model $C_V = g_V \cdot (a_{LL})_{SM}$ and $C_A = g_A \cdot (a_{LL})_{SM}$. The CVC hypothesis states that $g_V = 1$ and in the absence of new interactions one has $g_A \approx -1.27$ (Sec.III). The determination of the couplings A_{ij} and α_{ij} from experiments requires the constants g_S and g_T to be known, which can be calculated in various quark models of the nucleons (Herczeg, 2001).

E. Left-right symmetric models

The observations of parity violation in the weak interaction is embedded in the standard model by imposing left-handed fermions to transform like $SU_L(2)$ doublets whereas right-handed fermions transform as singlets. Extensions based on wider gauge symmetry groups, have been proposed to provide a natural framework for the understanding of the breaking of the left-right symmetry observed in weak interactions (Beg *et al.*, 1977; Mohapatra and Pati, 1975; Pati and Salam, 1973, 1974; Senjanovic and Mohapatra, 1975). The simplest left-right symmetric models are based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)$, in which, in addition to the transformations under $SU_L(2)$ above, the right-handed fermions transform now as doublets under $SU_R(2)$ whereas the left-handed ones transform as singlets.

The gauge symmetry of these models introduces additional bosons. The mass eigenstates of the predominantly left-handed bosons are denoted W_1 and Z_1 whereas those of the additional predominantly right-handed bosons are denoted W_2 and Z_2. The weak eigenstates, W_L and W_R, are linear combinations of the mass eigenstates

$$W_L = W_1 cos\zeta + W_2 sin\zeta \tag{29}$$
$$W_R = e^{i\omega}(-W_1 sin\zeta + W_2 cos\zeta). \tag{30}$$

where ζ is a mixing angle and ω is a CP-violating phase. The couplings of the weak bosons to the quarks and leptons of the first generation is given by (Herczeg, 2001)

$$\mathcal{L}_{LR} = (g_L/\sqrt{2})\left(\bar{u}_L\gamma_\mu V^L_{ud} d_L + \bar{\nu}_{Li}\gamma_\mu U^L_{ie} e_L\right) W_L$$
$$(g_R/\sqrt{2})\left(\bar{u}_R\gamma_\mu V^R_{ud} d_R + \bar{\nu}_{Rj}\gamma_\mu U^R_{je} e_R\right) W_R \tag{31}$$

where g_L and g_R are the gauge couplings associated with $SU_L(2)$ and $SU_R(2)$ respectively and V^L_{ud}, V^R_{ud}, U^L_{ie} and U^R_{je} are elements of mixing matrices for quarks and leptons which are relevant to the first generation. The interaction given in Eq. (31) contains only vector terms and it is seen to be invariant under left-right symmetry.

At the level of nucleons, the Hamiltonian which describes nuclear β-decay resulting from Eq. (31) contains V- and A-interactions, as in Eq. (10). The relation between the fundamental parameters of Eq. (31) and the effective couplings in Eq. (10) are (Herczeg, 2001)

$$a_{LL} \simeq g_L^2 V^L_{ud}/(8m_1^2) \tag{32}$$
$$a_{RR} \simeq a_{LL}(V^R_{ud}/V^L_{ud})(g_R^2/g_L^2)\ \delta \tag{33}$$
$$a_{LR} \simeq -a_{LL}e^{i\omega}(V^R_{ud}/V^L_{ud})(g_R/g_L)\ \zeta \tag{34}$$
$$a_{RL} \simeq -a_{LL}e^{i\omega}(g_R/g_L)\ \zeta \tag{35}$$

where $\delta = (m_1/m_2)^2$, with m_1 (m_2) the mass of the W_1 (W_2) boson.

In the simple limit of so-called manifest left-right symmetry, in which $g_R = g_L$, $V^R_{ud} = V^L_{ud}$ and $\omega = 0$ one has $a_{RR} = \delta \cdot a_{LL}$ and $a_{LR} = a_{RL} = -\zeta \cdot a_{LL}$. Substituting these in Eqs. (17-20) results in

$$C_V = g_V a_{LL}(1 - 2\zeta + \delta) \tag{36}$$
$$C'_V = g_V a_{LL}(1 - \delta) \tag{37}$$
$$C_A = g_A a_{LL}(1 + 2\zeta + \delta) \tag{38}$$
$$C'_A = g_A a_{LL}(1 - \delta) \tag{39}$$

Comparing C_i with C'_i it appears that, in the limit of no mixing ($\zeta \to 0$), parity violation arises solely from the difference between the masses of W_1 and W_2.

F. Leptoquark exchange

Leptoquarks are bosons which couple to quark-lepton pairs. As such they carry lepton numbers, baryon numbers and fractional charges. Only spin-zero (scalar) and spin-one (vector) leptoquarks occur (Herczeg, 2001).

Transitions in nuclear β-decay can be mediated by leptoquarks with charges $|Q| = 2/3$ and $|Q| = 1/3$. Figure 3 illustrates possible decay channels mediated by vector and scalar leptoquarks, denoted X and Y respectively.

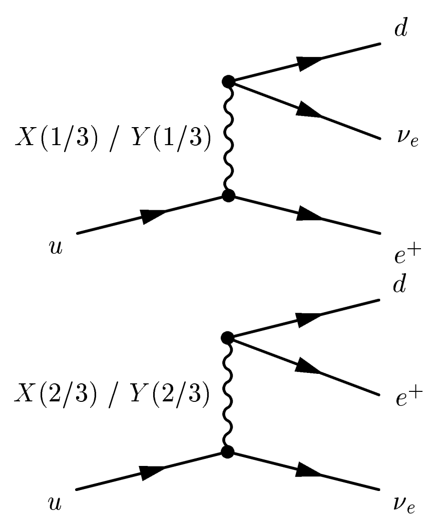

FIG. 3 Leptoquark exchanges contributing to nuclear β-decay. Top: $|Q| = 1/3$ leptoquarks; bottom: $|Q| = 2/3$ leptoquarks.

The four fermion interaction generated by the exchange of $X_{|Q|}$ and $Y_{|Q|}$ leptoquarks has the form (Herczeg, 1995a)[4]

$$\begin{aligned} H_{X(2/3)} &= \bar{u}\gamma_\mu(1+\gamma_5)\nu_e^L \\ &\times[f_{LL}\bar{e}\gamma_\mu(1+\gamma_5)d + f_{LR}\bar{e}\gamma_\mu(1-\gamma_5)d] \\ &+\bar{u}\gamma_\mu(1-\gamma_5)\nu_e^R \\ &\times[f_{RL}\bar{e}\gamma_\mu(1+\gamma_5)d + f_{RR}\bar{e}\gamma_\mu(1-\gamma_5)d] \\ &+\text{H.c.} \end{aligned} \tag{40}$$

$$\begin{aligned} H_{X(1/3)} &= \bar{d}^c\gamma_\mu(1+\gamma_5)\nu_e^L \\ &\times[h_{LL}\bar{e}\gamma_\mu(1+\gamma_5)u^c + h_{LR}\bar{e}\gamma_\mu(1-\gamma_5)u^c] \\ &+\bar{d}^c\gamma_\mu(1-\gamma_5)\nu_e^R \\ &\times[h_{RL}\bar{e}\gamma_\mu(1+\gamma_5)u^c + h_{RR}\bar{e}\gamma_\mu(1-\gamma_5)u^c] \\ &+\text{H.c.} \end{aligned} \tag{41}$$

$$\begin{aligned} H_{Y(2/3)} &= \bar{u}(1+\gamma_5)\nu_e^L \\ &\times[F_{LL}\bar{e}(1+\gamma_5)d + F_{LR}\bar{e}(1-\gamma_5)d] \\ &+\bar{u}(1-\gamma_5)\nu_e^R \\ &\times[F_{RL}\bar{e}(1+\gamma_5)d + F_{RR}\bar{e}(1-\gamma_5)d] \\ &+\text{H.c.} \end{aligned} \tag{42}$$

$$\begin{aligned} H_{Y(1/3)} &= \bar{d}^c(1+\gamma_5)\nu_e^L \\ &\times[H_{LL}\bar{e}(1+\gamma_5)u^c + H_{LR}\bar{e}(1-\gamma_5)u^c] \\ &+\bar{d}^c(1-\gamma_5)\nu_e^R \\ &\times[H_{RL}\bar{e}(1+\gamma_5)u^c + H_{RR}\bar{e}(1-\gamma_5)u^c] \\ &+\text{H.c.} \end{aligned} \tag{43}$$

The first subscript of the couplings indicates the neutrino chirality and the second indicates the chirality of the fourth fermion in the coupling. This Hamiltonian can be transformed to the four fermion interaction of the form given in Eq. (7) by a Fierz transformation (see *e.g.* Greiner and Müller, 1996). The relation between the coefficients C_i and C'_i in Eq. (7) and the couplings in Eqs. (40-43) resulting from the exchange of $X_{|Q|}$ and $Y_{|Q|}$ leptoquarks are summarized in Tables II and III (Herczeg, 1995a).

Notably, vector leptoquarks can generate V, A and S interactions whereas scalar leptoquarks can in addition generate T interactions.

	X(2/3)	X(1/3)
C_V	$g_V(f_{LL}+f_{RR})$	$g_V(-h_{LL}-h_{RR})$
C'_V	$g_V(f_{LL}-f_{RR})$	$g_V(-h_{LL}+h_{RR})$
C_A	$g_A(f_{LL}+f_{RR})$	$g_A(h_{LL}+h_{RR})$
C'_A	$g_A(f_{LL}-f_{RR})$	$g_A(h_{LL}-h_{RR})$
C_S	$2g_S(-f_{LR}-f_{RL})$	$2g_S(-h_{LR}+h_{RL})$
C'_S	$2g_S(-f_{LR}+f_{RL})$	$2g_S(-h_{LR}-h_{RL})$
C_T	0	0
C'_T	0	0

TABLE II Coefficients resulting from vector leptoquark exchange.

	Y(2/3)	Y(1/3)
$2C_V$	$g_V(-F_{LR}-F_{RL})$	$g_V(-H_{LR}-H_{RL})$
$2C'_V$	$g_V(-F_{LR}+F_{RL})$	$g_V(-H_{LR}+H_{RL})$
$2C_A$	$g_A(F_{LR}+F_{RL})$	$g_A(-H_{LR}-H_{RL})$
$2C'_A$	$g_A(F_{LR}-F_{RL})$	$g_A(-H_{LR}+H_{RL})$
$2C_S$	$g_S(-F_{LL}-F_{RR})$	$g_S(-H_{LL}-H_{RR})$
$2C'_S$	$g_S(-F_{LL}+F_{RR})$	$g_S(-H_{LL}+H_{RR})$
$2C_T$	$g_T(-F_{LL}-F_{RR})$	$g_T(H_{LL}+H_{RR})$
$2C'_T$	$g_T(-F_{LL}+F_{RR})$	$g_T(H_{LL}-H_{RR})$

TABLE III Coefficients resulting from scalar leptoquark exchange.

G. Higher-order corrections

Additional effects may become important when the precision of the measurements reaches a level below 10^{-2} to 10^{-3}. Such effects are called generically higher-order corrections and can have various sources like the possible presence of forbidden matrix elements due to the breakdown of the allowed approximation, the induced weak currents due to the hadronic structure of the nucleons and the radiative corrections of higher order. Other effects like the finite mass of the recoiling nucleus can affect some observables like the shape of the energy spectrum of electrons (Holstein, 1974, 1976) and can be of importance for specific experiments. Among the higher-order effects we focus briefly here on the induced weak currents due to their role to establish and test some of the symmetries of the weak interaction.

The fact that the strength of the weak interaction between quarks is not the same as in muon decay is further complicated in hadrons due to the presence of the strong interaction. In semi-leptonic processes this gives rise to the induced weak currents which can be observed by the departures of the experimental properties from their leading order description.

The structure of the vector and axial vector hadronic currents, consistent with Lorentz invariance and including recoil terms, has the general form (Fujii and Primakoff, 1959; Goldberger and Treiman, 1958; Weinberg, 1958)

[4] See Appendix A for the conventions on the metric.

$$V_\mu^h = \bar{p}\Big[g_V(q^2)\gamma_\mu + f_M(q^2)\sigma_{\mu\nu}\frac{q_\nu}{2M} + if_S(q^2)\frac{q_\mu}{m_e}\Big]n \quad (44)$$

$$A_\mu^h = \bar{p}\Big[g_A(q^2)\gamma_\mu\gamma_5 + f_T(q^2)\sigma_{\mu\nu}\gamma_5\frac{q_\nu}{2M} + if_P(q^2)\frac{q_\mu}{m_e}\gamma_5\Big]n \quad (45)$$

where $q_\mu = (p_i - p_f)_\mu$ is the four-momentum transfer and M and m_e are respectively the nucleon and the electron mass. The form factors g_V, g_A, f_i ($i = M, S, T, P$) are arbitrary functions of the Lorentz scalar q^2. The values of these form factors in the limit of zero momentum transfer, $q^2 \to 0$, are called the vector, axial-vector, weak magnetism, induced scalar, induced tensor, and induced pseudo-scalar couplings respectively. In particular $g_V = g_V(0)$ and $g_A = g_A(0)$ are the leading-order V and A couplings whereas the other terms are the induced weak currents.

The study of the symmetries of the induced currents introduced the concept of G-parity. A G-parity transformation is defined by a charge conjugation operation followed by a rotation by π around the y-axis in isospin space

$$G = Ce^{i\pi T_2} \quad (46)$$

This transformation is a symmetry of the strong interaction and it is interesting to study the properties of the terms in the currents above under G such as to determine, at least at the phenomenological level, whether all the terms allowed by Lorentz invariance are dynamically possible. By definition, vector currents with G-parity $+1$ and axial currents with G-parity -1 are called *first class* currents whereas those with the opposite parities are called *second class* currents (SCC) (Weinberg, 1958).

The dominant vector and axial currents, the weak magnetism and the induced pseudo-scalar belong to the first class whereas the induced scalar and the induced tensor are second class. The requirement that the hadronic V and A currents have a definite G-parity implies that SCC cannot exist, hence $f_S(q^2) = 0$ and $f_T(q^2) = 0$. Such requirement appears in the elaboration of a unified electroweak theory (Weinberg, 1958) and was a very strong motivation for the search of SCC. The tests performed so far indicate that the strengths of SCC are consistent with zero (Grenacs, 1985; Towner and Hardy, 1995).

The fact that the electromagnetic current between nucleons exhibits a similar isospin structure as the strangeness-conserving weak vector current led Feynman and Gell-Mann (1958) to postulate that these currents formed a multiplet of vector current operators. This was the first significant step toward a formal unification of the weak and electromagnetic interactions and a precursor of the $SU_L(2) \times U(1)$ gauge theory of electroweak interactions. One of the consequences of this hypothesis is the conservation of the vector current (CVC) with the result that $g_V(q^2) = 1$, independently of the nucleus. In other words, the vector coupling constant is not renormalized in the nuclear medium leading to the "universality" of the weak vector current. Another consequence of CVC is that, for β-transitions between analogue states, the weak magnetism form factor is related to the difference between the anomalous isovector magnetic moments of the respective nuclear states, while for non-analogue transitions it is related to the corresponding isovector M1 γ-decay rate.

The axial-vector current has no electromagnetic analogue and is not a conserved current. However, the hypothesis of a partially conserved axial current (PCAC) has been introduced as a valid symmetry in the limit of the pion mass tending to zero. One of the consequences of PCAC relates the induced pseudo-scalar form factor to the axial-vector form factor. In semi-leptonic processes, the pseudo-scalar coupling is multiplied by the mass of the charged lepton in the expression of the transition rate. For processes such as nuclear β-decay the pseudo-scalar term gives a negligible contribution whereas in muon capture the contribution is enhanced due to the larger muon mass. Muon capture processes have then served for the determination of the pseudo-scalar couplings (Gorringe and Fearing, 2004) and the tests of PCAC.

In summary, the study of the induced weak currents in nuclei has contributed to the establishment of relations between the symmetries of the electromagnetic currents and those of the weak currents and as such has played a crucial role in identifying and testing the symmetry structure of the electroweak theory. The three main consequences of the symmetry properties are *i)* the conserved vector current (CVC); *ii)* the partially conserved axial current (PCAC); *iii)* the absence of second class currents (SCC). They provide additional tests of the standard electroweak model in nuclear β-decay. The experimental constraints on the possible existence of SCC as well as the status of the tests of CVC and PCAC have been reviewed by Grenacs (1985), Towner and Hardy (1995) and Hardy and Towner (2005a), and are discussed in Sec. IV.A.1 and Sec. IV.F.

H. Correlation coefficients

The coupling constants C_i and C_i', which determine the dynamics of β-decay, have to be determined from experiments. Jackson, Treiman, and Wyld (1957b) calculated several decay rate distributions from the general Hamiltonian, Eq. (7), for allowed transitions including Coulomb corrections. The distribution in the electron and neutrino directions and in the electron energy from oriented nuclei is given by

$$\omega(\langle\mathbf{J}\rangle|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu = \\ \frac{F(\pm Z,E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \times \\ \frac{1}{2}\xi\left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e}\right. \\ +c\left[\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{3E_e E_\nu} - \frac{(\mathbf{p}_e\cdot\mathbf{j})(\mathbf{p}_\nu\cdot\mathbf{j})}{E_e E_\nu}\right]\left[\frac{J(J+1)-3\langle\mathbf{J}\cdot\mathbf{j}\rangle^2}{J(2J-1)}\right] \\ \left. +\frac{\mathbf{J}}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_e E_\nu}\right]\right\} \tag{47}$$

The distribution in electron and neutrino direction and electron polarization from non-oriented nuclei is given by

$$\omega(\boldsymbol{\sigma}|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu = \\ \frac{F(\pm Z,E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \times \\ \frac{1}{2}\xi\left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \boldsymbol{\sigma}\cdot\left[G\frac{\mathbf{p}_e}{E_e} + H\frac{\mathbf{p}_\nu}{E_\nu}\right.\right. \\ \left.\left. +K\frac{\mathbf{p}_e}{E_e+m}\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + L\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_e E_\nu}\right]\right\} \tag{48}$$

The distribution in the electron energy and angle and in the electron polarization from oriented nuclei is given by

$$\omega(\langle\mathbf{J}\rangle,\boldsymbol{\sigma}|E_e,\Omega_e)dE_e d\Omega_e = \\ \frac{F(\pm Z,E_e)}{(2\pi)^4} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e \times \\ \xi\left\{1 + b\frac{m}{E_e} + \frac{\mathbf{p}_e}{E_e}\cdot\left(A\frac{\langle\mathbf{J}\rangle}{J} + G\boldsymbol{\sigma}\right) + \boldsymbol{\sigma}\cdot\left[N\frac{\langle\mathbf{J}\rangle}{J}\right.\right. \\ \left.\left. +Q\frac{\mathbf{p}_e}{E_e+m}\left(\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}_e}{E_e}\right) + R\frac{\langle\mathbf{J}\rangle}{J}\times\frac{\mathbf{p}_e}{E_e}\right]\right\} \tag{49}$$

In Eqs. (47-49), E_e, p_e, and Ω_e denote the total energy, momentum, and angular coordinates of the β-particle and similarly for the neutrino; $\langle\mathbf{J}\rangle$ is the nuclear polarization of the initial nuclear state with spin $\mathbf{J}$; $\mathbf{j}$ is a unit vector in the direction of $\mathbf{J}$; E_0 is the total energy available in the transition; m is the electron rest mass; $F(\pm Z, E_e)$ is the Fermi-function and $\boldsymbol{\sigma}$ is the spin vector of the β-particle. The upper (lower) sign refers to β^- (β^+)-decay. The a, b, c, A, B, etc., are the correlation coefficients, the most relevant ones being listed in Appendix B. The coefficients c, H, K and L are mentioned here for completeness but are of no practical importance since there are no precise measurements of them relevant to test the weak interaction.

In decays leading to an intermediate unstable state in the daughter nucleus followed by γ, α or proton emission, the delayed particle carries part of the information of the decay according to Eqs. (47-49). These decays can also serve to determine the correlation coefficients (Holstein, 1974, 1976).

For a given correlation coefficient complementary information can be extracted from both the leading term and from its Coulomb correction (terms of order αZ). For pure Fermi or pure Gamow-Teller transitions the correlation coefficients become independent of the nuclear matrix elements avoiding the need to accurately know the details of the nuclear structure.

III. STATUS OF THE V-A THEORY

The determination of the couplings which enter the general β-decay Hamiltonian can be performed by considering accurate experimental results from correlation measurements in allowed transitions. The two most general analyses performed so far (Boothroyd *et al.*, 1984; Paul, 1970) have determined to which extent the presence of non-standard couplings were excluded by the experimental data. Both analyses were consistent with the *V-A* theory but allowed substantial deviations from it. Other adjustments realized later were either less general (Deutsch and Quin, 1995), excluded explicitly scalar and tensor contributions (Carnoy *et al.*, 1992), or were limited to some specific decays (Abele, 2000; Towner and Hardy, 2003).

In this section we present a new least-squares adjustment with the aim to update the status of the phenomenological *V-A* description of nuclear β-decay. The analysis is similar to the one performed by Boothroyd *et al.* (1984) with some modifications explained below. The inclusion of new experimental data with high precision improves significantly the determination of the standard couplings and the constraints on the exotic couplings.

A. General Assumptions

It is assumed that all transitions considered in this analysis can be described in the allowed approximation. The most general Hamiltonian describing nuclear β-decay is given in Eq. (7), which includes all possible Lorentz invariant operators (scalar, vector, axial-vector, tensor and pseudo-scalar). In this description, neutrinos are assumed to be massless, the interaction is considered to be local and to involve the fermion fields linearly. As indicated above, the pseudo-scalar contribution cancels in the non-relativistic description of the nucleons so that it is neglected from the expressions of the correlation parameters in allowed transitions (Jackson *et al.*, 1957b).

We will not restrict here the couplings C_i and C_i' to be all real, as has been the case for previous general analyses (Boothroyd *et al.*, 1984; Paul, 1970) although we consider such case as a particular framework.

The expressions of the correlation coefficients which are accessible to experiments can be calculated from the β-decay Hamiltonian, Eq. (7), and can be expressed as functions of the coupling constants and the nuclear matrix elements (Jackson *et al.*, 1957b). Those of the parameters considered here are presented in the Appendix B. In the fits discussed below, the expressions of the correlation parameters a, A, B, G, D and R have been divided by the term $(1 + b\langle W^{-1}\rangle)$, where W is the total energy of the beta particle. In particular this has also been applied to the angular correlation coefficient a and not only to parameters resulting from measurements of asymmetries.

We have considered the following experimental inputs: the Fierz interference term b_F from the $\mathcal{F}t$-values of the super-allowed $0^+ \rightarrow 0^+$ transitions; the lifetime of the neutron, τ_n; the electron-neutrino angular correlation, a; the Fierz interference term, b; the angular distribution of electrons from polarized neutrons or from polarized nuclei, A; the angular distribution of neutrinos from polarized neutrons, B; the electron longitudinal polarization, G in units of v/c; the ratio between the longitudinal polarizations of electrons emitted from pure Fermi and pure Gamow-Teller transitions, P_F/P_{GT}; the ratio between the polarizations of electrons emitted from polarized nuclei along two directions relative to the nuclear spin, P^-/P^+; the ratio between the polarizations of electrons emitted from polarized and unpolarized nuclei, P^-/P^0; the time reversal violating triple correlation coefficients, D and R.

The $\mathcal{F}t$-values of super-allowed transitions and the neutron lifetime depend both on the weak interaction coupling $G_F V_{ud}/\sqrt{2}$ but not so their ratio. The neutron lifetime was then expressed in a ratio relative to the $\mathcal{F}t$ of super-allowed transitions. The average $\mathcal{F}t$-values used in the calculations are: $\mathcal{F}t = (3073.5 \pm 1.2)$ s for the fits in which the assumptions result in $b_F = 0$ (Hardy and Towner, 2005a) or $\mathcal{F}t = (3072.5 \pm 2.2)$ s for the fits where b_F can be non zero (Towner, 2005).

B. Least-squares method

The expressions of the correlation parameters depend non-linearly on a set of M parameters $a_k, k = 1, \ldots, M$. Given the model functions $y(x,\boldsymbol{a})$ one defines the merit function χ^2 which is minimized to determine the best-fit parameters. The χ^2 merit function is defined by

$$\chi^2 = \sum_{i=1}^{N} \left[\frac{y_i - y(x_i, a)}{\sigma_i} \right]^2 \qquad (50)$$

In the present case x_i is just a label for the input measurement i; y_i is the measured value and σ_i is the corresponding (1σ) experimental error. The functions $y(x,\boldsymbol{a})$ correspond to the theoretical expressions of the correlation parameters given in the Appendix B. The parameters $\boldsymbol{a}$ are defined below as ratios of the different couplings C_i and C_i'. The principle of non-linear χ^2 minimization can be found elsewhere (Eadie *et al.*, 1971). For the present adjustment we have used the Levenberg-Marquardt method which has become a standard for non-linear least-squares algorithms (Press *et al.*, 2002).

C. Selection of data

The experimental data used in the least-squares adjustment is given in Tables IV and V.

Table IV contains only data from neutron decay and the columns give respectively: the measured parameter, the experimental value, the experimental error (1σ) on the value, an estimate of the average $\langle W^{-1}\rangle$, where W the β particle total energy in units of $m_e c^2$, and the reference for the quoted value. The parameter λ in this table is defined as $\lambda = (A - B)/(A + B)$.

Table V contains data from pure Fermi and pure Gamow-Teller transitions. The columns list respectively: the parent nucleus in the transition, the atomic number Z of the daughter nucleus, the initial (J) and final (J') spins of the transition, the transition type, the measured parameter, the experimental value, the experimental error on the value, an estimate of the average $\langle W^{-1}\rangle$ and the reference for the quoted value. For the relative beta longitudinal polarization measurements, the values listed in Table V are not directly the values of the measured polarization ratios but the ratio between the experimental result (which is a ratio between longitudinal polarizations) and its corresponding value expected within the V-A theory. This is of no concern for the ratio P_F/P_{GT} obtained with unpolarized nuclei, in which case the expected ratio within the V-A theory is unity, but applies to the other two cases where the measured ratios depend on the experimental conditions.

The following selection criteria have been adopted: *i)* except for the neutron decay, only pure Fermi and pure Gamow-Teller transitions have been considered. The inclusion of data from other mixed transitions like ^{19}Ne, ^{21}Na or ^{35}Ar would require to review the relevant spectroscopic data of those transitions. Such data is necessary to calculate the expected values of the correlation coefficients within the V-A theory, with sufficient accuracy; *ii)* when in a given transition several values for a correlation coefficient were available, all inputs having an error which was at least ten times larger than the error of the most precise measurement have been eliminated. Exceptions to this rule concern some cases where the quoted values for a given parameter have been published for different energies of the β particles; *iii)* all experimental data from transitions having a "large" $\log(ft)$ value have been eliminated. Such slow transitions require a closer look to the validity of the description within the allowed approximation and to the effects of recoil order corrections. The phenomenological classification of transitions based on the $\log(ft)$ values considers as *allowed* those having values in the range $\log(ft) = 5.7 \pm 1.1$ (deShalit and Feshbach, 1974). We therefore eliminated

TABLE IV Experimental data from neutron decay used in the least-squares fits

parameter	value	error	$\langle W^{-1}\rangle$	Reference
a	-0.0910	0.0390	0.604	Grigoriev *et al.* (1968)
	-0.1017	0.0051	0.655	Stratowa *et al.* (1978)
	-0.1054	0.0055	0.655	Byrne *et al.* (2002)
A	-0.1040	0.0110	0.716	Krohn and Ringo (1975)
	-0.1160	0.0110	0.537	Krohn and Ringo (1975)
	-0.1200	0.0100	0.594	Erozolimskii *et al.* (1979)
	-0.1140	0.0120	0.724	Erozolimskii *et al.* (1979)
	-0.1120	0.0062	0.561	Erozolimskii *et al.* (1979)
	-0.1146	0.0019	0.581	Bopp *et al.* (1986)
	-0.1189	0.0012	0.534	Abele *et al.* (1997)
	-0.1160	0.0015	0.582	Liaud *et al.* (1997)
	-0.1135	0.0014	0.558	Yerozolimsky *et al.* (1997)
	-0.1189	0.0008	0.534	Abele *et al.* (2002)
B	0.9950	0.0340	0.655	Erozolimsky *et al.* (1970)
	0.9894	0.0083	0.554	Kuznetsov *et al.* (1995)
	0.9801	0.0046	0.594	Serebrov *et al.* (1998)
λ	-1.2686	0.0047	0.581	Mostovoi *et al.* (2001)
τ_n	891.00	9.00	0.655	Spivak (1988)
	877.00	10.00	0.655	Paul and et al. (1989)
	887.60	3.00	0.655	Mampe *et al.* (1989)
	888.40	3.30	0.655	Nesvishevsky *et al.* (1992)
	882.60	2.70	0.655	Mampe *et al.* (1993)
	889.20	4.80	0.655	Byrne *et al.* (1996)
	885.40	1.00	0.655	Arzumanov *et al.* (2000)
	886.80	3.40	0.655	Dewey *et al.* (2003)
	878.50	0.76	0.655	Serebrov *et al.* (2005a)
D	-0.00270	0.00500	0.655	Erozolimskii *et al.* (1974)
	-0.00110	0.00170	0.650	Steinberg *et al.* (1976)
	0.00220	0.00300	0.619	Erozolimskii *et al.* (1978)
	-0.00060	0.00130	0.655	Lising *et al.* (2000)
	-0.00024	0.00071	0.602	Soldner *et al.* (2004)

all inputs from transitions having $\log(ft) > 6.8$. This concerns ^{22}Na ($\log(ft) = 7.4$), ^{32}P ($\log(ft) = 7.9$) and ^{60}Co ($\log(ft) = 7.5$), and excludes 61 inputs which were previously used in the analysis by Boothroyd *et al.* (1984). These authors concluded that the question on the validity of the allowed approximation had to be reconsidered when including more accurate experimental data. In this context, a recent measurement of the $\beta-\gamma$ directional correlation (Bowers *et al.*, 1999) addresses the competition between the suppressed allowed matrix elements and the relevant forbidden ones in the decay of ^{22}Na.

D. Results

1. Real couplings fit

The first framework involves a maximum of seven parameters a_k, assumed all to be real. Expressed as a function of the couplings these parameters are defined as

TABLE V Data from measurements in nuclear decays used in the least-squares fits

isotope	Z	J	J'	type	parameter	value	error	$\langle W^{-1}\rangle$	Reference
^{6}He	3	0	1	GT/β^-	a	-0.33000	0.01000	0.286	Johnson *et al.* (1961)
						-0.33080^a	0.00300	0.286	Johnson *et al.* (1963)
						-0.31900	0.02800	0.199	Vise and Rustad (1963)
^{8}Li	4	2	2	GT/β^-	R	0.00090	0.00220	0.062	Huber *et al.* (2003)
^{12}B	6	1	0	GT/β^-	G	-0.98000	0.06000	0.055	Lipnik *et al.* (1962)
^{12}N	6	1	0	GT/β^+	P^-/P^+	1.00060	0.00340	0.079	Thomas *et al.* (2001)
^{14}O	7	0	0	F/β^+	G	0.97000	0.19000	0.338	Hopkins *et al.* (1961)
^{14}O/^{10}C	7/5			F-GT/β^+	P_F/P_{GT}	0.99960	0.00370	0.292	Carnoy *et al.* (1991)
^{18}Ne	9	0	0	F/β^+	a	1.06000	0.09500	0.289	Egorov *et al.* (1997)
^{23}Ne	11	2.5	1.5	GT/β^-	a	-0.37000	0.04000	0.243	Allen *et al.* (1959)
						-0.33000	0.03000	0.243	Carlson (1963)
^{26}Al/^{30}P	12/14			F-GT/β^+	P_F/P_{GT}	1.00300	0.00400	0.189	Wichers *et al.* (1987)
^{32}Ar	17	0	0	F/β^+	a	0.99890	0.00650	0.210	Adelberger *et al.* (1999)
^{38m}K	18	0	0	F/β^+	a	0.99810	0.00480	0.161	Gorelov *et al.* (2005)
^{68}Ga	30	1	0	GT/β^+	G	0.99000	0.09000	0.307	Ullman *et al.* (1961)
^{107}In	48	4.5	3.5	GT/β^+	P^-/P^+	0.92600	0.04100	0.311	Severijns *et al.* (1993)
					P^-/P^0	0.98980	0.00820	0.311	Camps (1997)
^{114}In	50	1	0	GT/β^-	b	0.05000	0.02000	0.399	Daniel and Panussi (1961)
						0.00500	0.02200	0.399	Daniel *et al.* (1964)
					A	-1.01300	0.02400	0.662	Severijns (1989)
					G	-0.96900	0.03700	0.449	van Klinken (1966)
^{127}Te	53	1.5	2.5	GT/β^-	A	0.56900	0.05100	0.721	Vanneste (1986)
^{129}Te	53	1.5	2.5	GT/β^-	A	0.64500	0.05900	0.528	Vanneste (1986)
^{133}Xe	55	1.5	2.5	GT/β^-	A	0.59800	0.07300	0.818	Vanneste (1986)
several		0	0	F/β^+	b_F	0.0001	0.0026		Hardy and Towner (2005a)

[a]Value quoted by F. Gluck (1998) after including radiative corrections.

$$a_1 = C_A/C_V, \qquad a_2 = C_S/C_V, \qquad a_3 = C_T/C_A, \quad (51)$$
$$a_4 = C'_V/C_V, \qquad a_5 = C'_A/C_A, \qquad a_6 = C'_S/C_V,$$
$$a_7 = C'_T/C_A$$

Several subsets of these parameters can be considered as free parameters, corresponding to different assumptions in terms of the presence of exotic couplings and of maximal parity violation.

For comparison with previous work (Boothroyd *et al.*, 1984) the inputs on the D and R coefficients, which are mainly sensitive to imaginary couplings, have been excluded from the data subset in this first framework.

Case 1: Standard one-parameter fit. The simplest model to be considered corresponds to the *V-A* limit. Here it is assumed that $C'_V/C_V = C'_A/C_A = 1$, and that the scalar and tensor couplings are zero. The only free parameter is C_A/C_V. This ratio is determined by the neutron data as the coefficients from the considered nuclear transitions do not depend on it. The fit of the corresponding 26 experimental inputs with that single free parameter gives $C_A/C_V = -1.27293(46)$, where the error is only statistical at 1σ. For this fit one obtains $\chi^2 = 74.08$ for $\nu = 25$ degrees of freedom. It is however interesting to observe the effect of excluding the single recent measurement of the neutron lifetime (Serebrov *et al.*, 2005a) from the input data set. The fit of the remaining 25 data gives $C_A/C_V = -1.26992(63)$ with $\chi^2 = 25.86$ for $\nu = 24$ degrees of freedom. Accounting for the ± 1.2 s error on the $\mathcal{F}t$-value results in

$$C_A/C_V = -1.26992(69) \qquad (52)$$

This value has an error which is more than an order of magnitude smaller than that obtained by Boothroyd *et al.* (1984) and a factor of 4.2 smaller than the presently recommended value $\lambda = -1.2695(29)$ (Eidelman *et al.*, 2004).

Case 2: Left-handed three-parameter fit. This model allows the presence of scalar and tensor couplings with the constraints $C'_V/C_V = 1$, $C'_A/C_A = 1$, $C'_S/C_V = C_S/C_V$, and $C'_T/C_A = C_T/C_A$. The three free parameters are C_A/C_V, C_S/C_V and C_T/C_A. The minimization of the χ^2 converges to a single minimum with the following values and 1σ statistical errors: $C_A/C_V = -1.27296(69)$, $C_S/C_V = 0.00045(127)$ and $C_T/C_A = 0.0086(31)$, implying a non-zero tensor component. At this minimum $\chi^2 = 82.45$ for $\nu = 47$ degrees of freedom. Excluding again the recent neutron lifetime measurement leads however to a significantly different minimum, with $\chi^2 = 40.91$ for $\nu = 46$ degrees of freedom. The values of the parameters at this minimum are then

$$C_A/C_V = -1.26994(82) \qquad (53)$$
$$C_S/C_V = 0.0013(13) \qquad (54)$$
$$C_T/C_A = 0.0036(33) \qquad (55)$$

where the errors include the effect of the ± 1.2 s error on the $\mathcal{F}t$-value.

For C_A/C_V the error is again more than an order of magnitude smaller than that obtained by Boothroyd *et al.* (1984). The error on C_S/C_V is a factor of about 2 smaller. However, the error on C_T/C_A is larger by a factor of 4. This is attributed to the exclusion of the 61 data points from ^{22}Na, ^{32}P and ^{60}Co, which are all three pure Gamow-Teller transitions. The 95.5% confidence level (CL) limits are obtained by taking 2σ of the quoted values as the correlations between the parameters are small.

Case 3: Vector Axial-vector three-parameter fit. In this model the scalar and tensor couplings are excluded. The three remaining parameters are C_A/C_V, C'_V/C_V and C'_A/C_A which all contain standard couplings. Allowing these parameters to be free provides a test of the degree of maximal parity violation with vector and axial couplings. The minimization results in two equivalent minima. Excluding the recent neutron lifetime measurement from the data set leads to $\chi^2 = 40.93$ for $\nu = 46$ degrees of freedom. The central values of the parameters at these minima are

	min.A	min.B
C_A/C_V	-1.2702	-1.2701
C'_V/C_V	0.920	1.087
C'_A/C_A	0.920	1.087

The situation is similar to that encountered earlier by Boothroyd *et al.* although the relative distance between the minima is here significantly smaller. Due to the correlations between the parameters the quotation of independent confidence intervals requires the χ^2 hyper-surface to be scanned. Figure 4 shows the projection of the iso-χ^2 contours onto the plane of the parameters C'_V/C_V and C_A/C_V. The lines around the minima correspond to the 1σ, 2σ and 3σ contours of the confidence regions, obtained by varying the values of all three parameters near the minima. The corresponding global limits of the confidence regions, at the 2σ level, are

$$-1.372 < C_A/C_V < -1.180 \qquad (56)$$
$$0.857 < C'_V/C_V < 1.169 \qquad (57)$$
$$0.868 < C'_A/C_A < 1.153 \qquad (58)$$

The limits on C'_A/C_A are similar to those obtained earlier (Boothroyd *et al.*, 1984) whereas the intervals for the other two parameters have significantly been reduced.

Case 4: Right-handed Scalar and Tensor three-parameter fit. In this model the three free parameters are C_A/C_V, C_S/C_V and C_T/C_A with the conditions $C'_V/C_V = 1$, $C'_A/C_A = 1$, $C'_S/C_V = -C_S/C_V$, and $C'_T/C_A = -C_T/C_A$. This corresponds to the assumption of left-handed couplings in the standard sector and right-handed couplings for the scalar and tensor. The

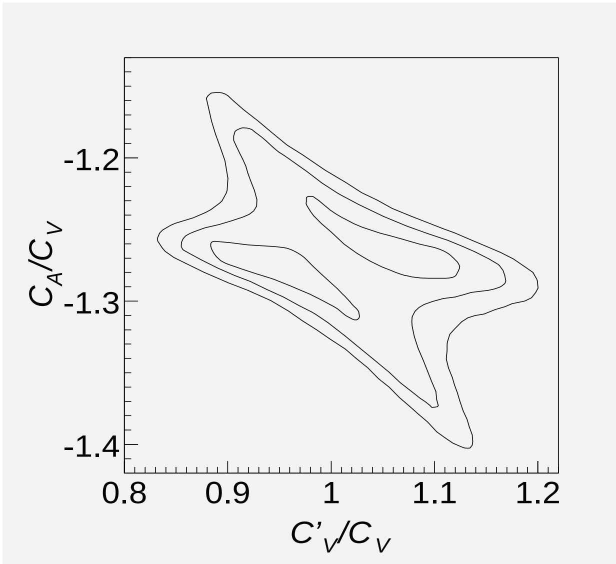

FIG. 4 Contours of constant χ^2 around the two minima obtained for the fit case 3. The lines correspond to 1σ, 2σ and 3σ confidence levels.

minimization of the χ^2 converges to two minima. Again, excluding the recent neutron lifetime measurement leads to $\chi^2 = 39.96$ for $\nu = 46$ degrees of freedom. The central values of the parameters at the minima are

	min.A	min.B
C_A/C_V	-1.2689	-1.2689
C_S/C_V	0.033	-0.033
C_T/C_A	0.052	-0.052

The two minima differ only by the signs of the scalar and tensor couplings which change simultaneously. Such a scenario has recently been considered in the analysis of selected data from neutron decay (Mostovoi *et al.*, 2000). Although the technique used there for the determination of the couplings differs from the one presented here, the conclusions regarding the scalar and tensor couplings are similar, namely that for each minimum the two couplings have the same sign. However, the independent quotation of CL intervals for each parameter requires both minima to be considered simultaneously and to account for the correlations with C_A/C_V. The 2σ confidence regions obtained by scanning the χ^2 hyper-surfaces are

$$-1.272 < C_A/C_V < -1.265 \tag{59}$$

$$-0.067 < C_S/C_V < 0.067 \tag{60}$$

$$-0.081 < C_T/C_A < 0.081 \tag{61}$$

The contours of the confidence regions for the three pairs of parameters are shown in Figs. 5, 6 and 7. Again, the lines around each minimum correspond to the three levels of constant χ^2 : $\chi_0^2 + 1$, $\chi_0^2 + 2^2$ and $\chi_0^2 + 3^2$, where χ_0^2 is the value of the χ^2 at the minimum. The global confidence region for each parameter is obtained by varying the values of the other two parameters around the minima.

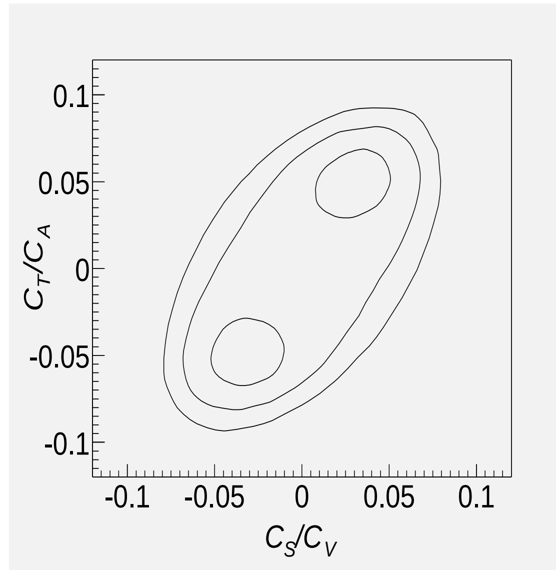

FIG. 5 Projections of contours of constant χ^2 on the plane of parameters C_S/C_V and C_T/C_A for the fit case 4.

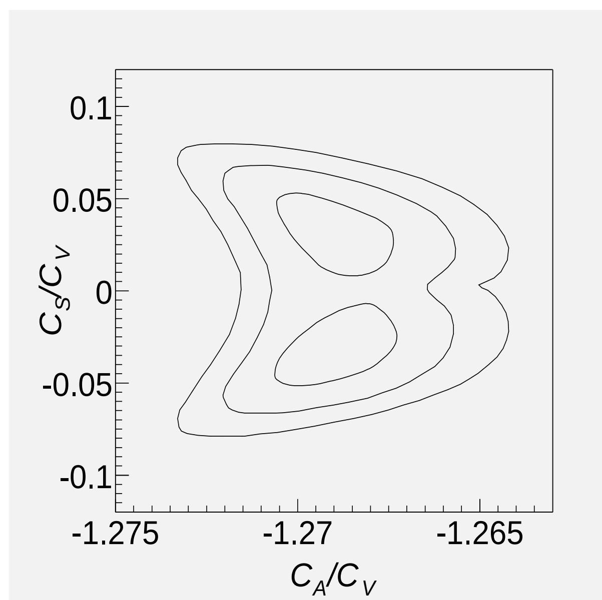

FIG. 6 Projections of contours of constant χ^2 on the plane of parameters C_A/C_V and C_S/C_V for the fit case 4.

Case 5: Five-parameter fit. A first generalization of the case 2 above consists in relaxing the constraint on the exotic couplings, allowing C'_S be different from C_S and C'_T from C_T. In this model the five free parameters are then C_A/C_V, C_S/C_V, C'_S/C_V, C_T/C_A and C'_T/C_A keeping the condition $C'_V/C_V = C'_A/C_A = 1$. When the recent neutron lifetime is excluded from the data,

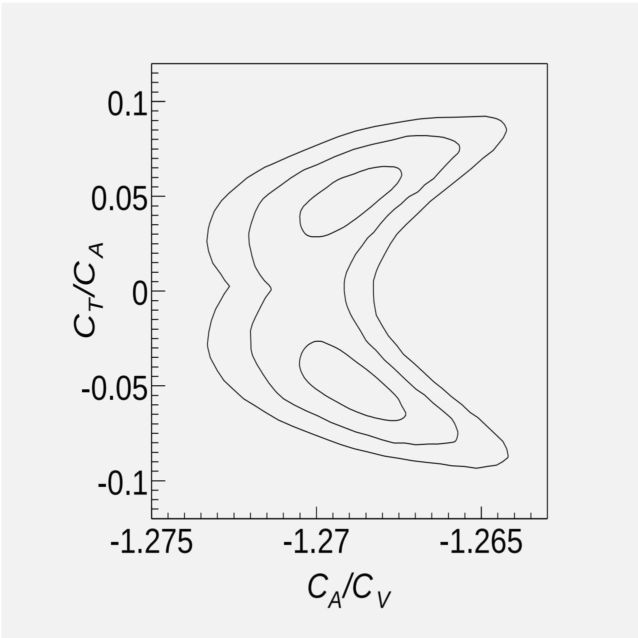

FIG. 7 Projections of contours of constant χ^2 on the plane of parameters C_A/C_V and C_T/C_A for the fit case 4.

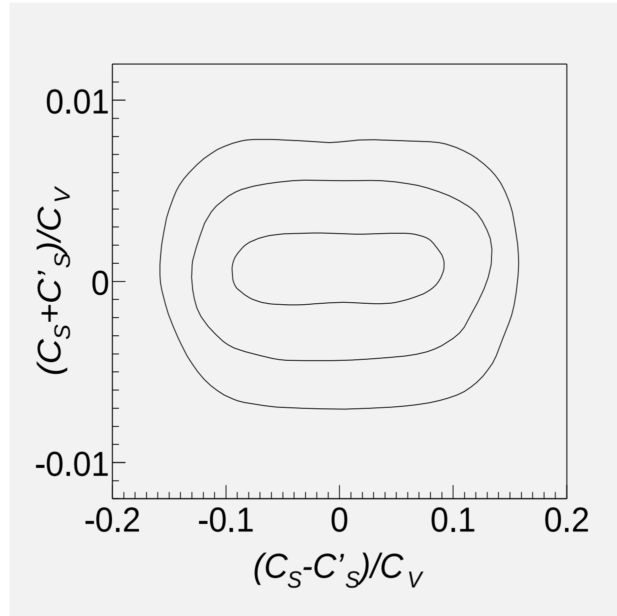

FIG. 8 Projections of contours of constant χ^2 for the combination of parameters $(C_S - C'_S)/C_V$ and $(C_S + C'_S)/C_V$.

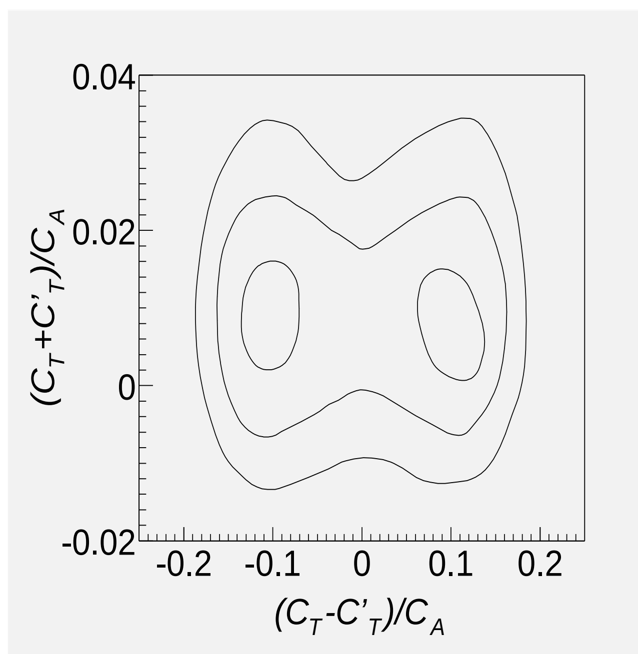

FIG. 9 Projections of contours of constant χ^2 for the combination of parameters $(C_T - C'_T)/C_A$ and $(C_T + C'_T)/C_A$.

two equivalent minima are found with $\chi^2 = 38.67$ for $\nu = 44$ degrees of freedom. At each minimum the signs of C_S/C_V and C_T/C_A are the same but opposite to those of C'_S/C_V and C'_T/C_A. The 2σ intervals obtained from the projections of the χ^2 hyper-surface are

$$-1.272 < C_A/C_V < -1.265 \tag{62}$$

$$-0.064 < C_S/C_V < 0.066 \tag{63}$$

$$-0.064 < C'_S/C_V < 0.065 \tag{64}$$

$$-0.077 < C_T/C_A < 0.086 \tag{65}$$

$$-0.077 < C'_T/C_A < 0.087 \tag{66}$$

Because of the correlations between C_S and C'_S and between C_T and C'_T, it is interesting to consider here the exclusion plots associated with the differences and the sums of these coefficients. This is also useful for a direct comparison with some experiments because the differences and sums of scalar and tensor couplings enter several correlation coefficients. The exclusion plots associated with this case are shown in Figs. 8 and 9.

Case 6: Seven-parameter fit. With the definition of parameters indicated above, Eq. (51), the most general fit is obtained by allowing all seven parameters to be free. However, when the number of parameters increases the search for equivalent minima is more difficult, the convergence is less robust and several local minima with similar χ^2 can be found. When considering the correlation between the parameters, the present case combines actually the cases 3 and 5 considered above. It is nevertheless possible to scan the χ^2 hyper-surface by varying all parameters to obtain the 2σ confidence level for each parameter. The outcome of such scan results in the following limits

$$-1.40 < C_A/C_V < -1.17 \quad (67)$$
$$0.87 < C'_V/C_V < 1.17 \quad (68)$$
$$0.86 < C'_A/C_A < 1.16 \quad (69)$$
$$-0.065 < C_S/C_V < 0.070 \quad (70)$$
$$-0.067 < C'_S/C_V < 0.066 \quad (71)$$
$$-0.076 < C_T/C_A < 0.090 \quad (72)$$
$$-0.078 < C'_T/C_A < 0.089 \quad (73)$$

It is seen that the surface $\chi^2 = \chi_0^2 + 2^2$ corresponding to the 95.5% CL region encloses the *V-A* assumptions, $C_S = C'_S = C_T = C'_T = 0$ and $C'_V/C_V = C'_A/C_A = 1$.

2. Imaginary couplings fit

When allowing for the presence of imaginary phases in the couplings, the total number of real parameters doubles with respect to the case in which all couplings are assumed to be real. In this second framework there are then 14 real parameters.

The most sensitive input data to imaginary parts in the couplings are the D and R triple correlation coefficients and there are actually only two such coefficients in the input data as far as the dependence on the couplings is concerned. It is then necessary to make additional assumptions in order to determine possible imaginary parts while achieving also a robust convergence to a minimum.

Case 7: Two-parameter fit with axial and vector couplings. The triple correlation coefficient D in a mixed transition is particularly sensitive to a possible phase between the two standard couplings C_V and C_A. The experimental results of such measurements are generally interpreted assuming $C_S = C'_S = C_T = C'_T = 0$, $C'_V/C_V = 1$ and $C'_A/C_A = 1$. Under these assumptions there remains only two parameters which are the real and imaginary parts of the ratio C_A/C_V. Here again, only the neutron data contributes to the determination of these parameters. Including all the 31 neutron data the minimization converges to a minimum with $\chi^2 = 75.25$ for $\nu = 29$ degrees of freedom whereas excluding the recent measurement of the neutron lifetime results in $\chi^2 = 27.03$ for $\nu = 28$. In both cases the values of the real part of C_A/C_V are identical to those obtained for the case 1 and both fits give for the imaginary part

$$\mathrm{Im}(C_A/C_V) = -0.0012(19) \quad (74)$$

Case 8: Single-parameter fit with imaginary tensor couplings. The other parameter sensitive to the possible presence of imaginary couplings is the R triple correlation. The only input data considered here arises from the decay in ^{8}Li. This decay is known to proceed by a predominantly Gamow-Teller transition which is then driven by the axial and eventually tensor couplings. It can here be assumed that all the couplings are left-handed (*i.e.* $C'_i = C_i$) and real except for C_T/C_A. As the determination of the imaginary part of C_T/C_A is solely determined by the R triple correlation, the result is independent of assumptions on the other parameters leading to the following value and 1σ error

$$\mathrm{Im}(C_T/C_A) = 0.0014(33) \quad (75)$$

It is interesting to notice that the uncertainty on the imaginary part of the tensor coupling is similar to that obtained on the real part in the most constrained fit, Eq. (55).

E. Conclusions

This section provided a quantitative summary of the experimental progress achieved over the past two decades. The values on the standard couplings and the constraints on exotic couplings have significantly been improved due to precision data from neutron decay, from measurements of relative longitudinal polarization of beta particles and of beta-neutrino correlations in nuclear decays. However, the recent measurement of the neutron lifetime (Serebrov *et al.*, 2005a) strongly affects the consistency of the fits and the values or ranges of the parameters. This obviously calls for an urgent confirmation or clarification of that experimental result.

The general fit with seven free real parameters (case 6) results in the following 95.5% CL limits for the exotic couplings,

$$|C_S/C_V| < 0.070 \quad (76)$$
$$|C'_S/C_V| < 0.067 \quad (77)$$
$$|C_T/C_A| < 0.090 \quad (78)$$
$$|C'_T/C_A| < 0.089 \quad (79)$$

Considering that $|C_A/C_V| \approx 1.27$ it appears from the results above that, in absolute terms, the limits on the amplitudes of tensor contributions are a factor of about two larger than those on the scalar contributions.

The fit with the three real parameters C_A/C_V, C'_V/C_V and C'_A/C_A (case 3) results in the following 95.5% CL limits for the standard couplings,

$$-1.372 < C_A/C_V < -1.180 \quad (80)$$
$$0.857 < C'_V/C_V < 1.169 \quad (81)$$
$$0.868 < C'_A/C_A < 1.153 \quad (82)$$

The limits on the imaginary parts of C_A/C_V and of C_T/C_A are almost independent of the constraints on other parameters under the assumptions considered above.

IV. EXPERIMENTAL TESTS

This section gives an overview of recent as well as ongoing and planned experiments in beta decay to test symmetries of the standard electroweak model and to search for new physics. We will concentrate here on experiments and projects that were ongoing or started after previous reviews of this field (Abele, 2000; Deutsch and Quin, 1995; Herczeg, 2001; van Klinken, 1996; Towner and Hardy, 1995; Yerozolimsky, 2000). Other recent reviews can be found in Erler and Ramsey-Musolf (2005) and Nico and Snow (2005).

First, the status and prospects for testing the unitarity of the quark mixing matrix will be discussed. This will be followed by an overview of searches for possible scalar and/or tensor type contributions to the weak interaction. Thereafter, the present situation with respect to the discrete symmetries of parity and time reversal will be reviewed. Finally, the direct searches for the electron neutrino mass will be discussed and the status of CVC and second class currents will briefly be presented.

A. Unitarity of the CKM quark mixing matrix

The CKM matrix (see Sec. II.B) relates the quark weak interaction eigenstates to the quark mass eigenstates and, as such, is a unitary matrix, *i.e.*

$$\sum_k V^*_{ki} V_{kj} = \delta_{ij}. \tag{83}$$

As up to now only the matrix elements V_{ud} and V_{us} have been determined with sub-percent precision, the most precise test of unitarity to date is obtained from the first row of the matrix, *i.e.*

$$\sum_i V^2_{ui} = V^2_{ud} + V^2_{us} + V^2_{ub} \qquad (i = d, s, b) \tag{84}$$

which should be equal to unity. The leading element, V_{ud}, depends only on the quarks in the first generation and can therefore be determined most precisely. The V_{us} matrix element is obtained from K decays. The third matrix element, V_{ub}, is obtained from B meson decays (Battaglia and Gibbons, 2004). If the CKM-matrix would turn out to be non-unitary this could point either to the existence of a fourth generation of fermions or to other new physics beyond the standard model, such as right-handed currents or non-V, A contributions to the weak interaction (see Hardy and Towner, 2005a,b).

The V_{ud} element can be deduced from the $\mathcal{F}$t values of superallowed $0^+ \to 0^+$ pure Fermi β transitions, from neutron decay and from pion beta decay. Combining each of these three values for V_{ud} with the two other matrix elements just mentioned then yields three almost independent tests of the unitarity of this matrix. We will review here the current status of these.

1. Superallowed Fermi transitions

Currently, the $\mathcal{F}$t value of eight superallowed $0^+ \to 0^+$ pure Fermi transitions, ^{14}O, ^{26}Al^m, ^{34}Cl, ^{38}K^m, ^{42}Sc, ^{46}V, ^{50}Mn and ^{54}Co, has been determined with a precision better than 1×10^{-3} and of four others, ^{10}C, ^{22}Mg, ^{34}Ar and ^{74}Rb with a precision better than 4×10^{-3} (Hardy and Towner, 2005b; Hardy *et al.*, 1990; Towner and Hardy, 2003).

The relation between the $\mathcal{F}$t value and V_{ud} is

$$\mathcal{F}t \equiv ft\,(1+\delta_R)\,(1-\delta_C) = \frac{K}{2\,G_F^2\,V_{ud}^2\,(1+\Delta_R^V)} \tag{85}$$

where f is the statistical rate function (see e.g. Appendix A in Hardy and Towner (2005b)) and

$$t = \frac{t_{1/2}}{BR}\left(1 + \frac{\varepsilon}{\beta^+}\right) \tag{86}$$

is the partial half-life for the transition that is obtained from the half-life, $t_{1/2}$, of the parent nucleus corrected for the branching ratio, BR, of the transition and for electron capture, ε/β^+. Note that the right hand side of Eq. (85) contains only fundamental constants and parameters determined by the weak interaction, while the left hand side contains the experimentally determined quantities and calculated nuclear corrections. The determination of the ft-value for a specific transition requires advanced spectroscopic methods as the half-life, the branching ratio as well as the transition energy, Q_{EC}, which is required to calculate f, have to be known with good precision.

Further, δ_R and Δ_R^V are the transition-dependent and nucleus-independent radiative corrections, while δ_C is the isospin symmetry-breaking correction. These must be calculated. The transition-dependent radiative correction δ_R can be split into a nuclear structure independent part, $\delta_R^{'}$, and a nuclear structure dependent part, δ_{NS}, with $\delta_R = \delta_R^{'} + \delta_{NS}$. The first is calculated from QED (Jaus and Rasche, 1987; Sirlin, 1967, 1987; Sirlin and Zucchini, 1986; Towner and Hardy, 2002) and is currently evaluated up to order $Z^2\alpha^3$, assigning an uncertainty equal to the magnitude of this order $Z^2\alpha^3$ contribution as an estimate of the error made by stopping the calculation there. For the twelve above mentioned transitions the values of δ_R' range from 1.39% to 1.65% (Towner and Hardy, 2002). The nuclear structure dependent part, δ_{NS}, was calculated in the nuclear shell model with effective interactions and ranges from +0.03% to −0.36% (Towner and Hardy, 2002). For the nucleus-independent correction the currently adopted value is $\Delta_R^V = 0.0240(8)$ (Sirlin, 1995; Towner and Hardy, 2002). Several independent calculations were performed for the isospin symmetry-breaking correction δ_C (Barker, 1992; Ormand and Brown, 1995; Sagawa, Van Giai, and Suzuki, 1996; Towner and Hardy, 2002; Towner, Hardy, and Harvey, 1977; Wilkinson, 2002, 2004). As only the calculations by

Ormand and Brown (1995) and by Towner and Hardy (2002) are constrained by experiments, thus offering an independent means to access their reliability, only these are usually retained. They are in reasonably good agreement, yielding values from about 0.2% to 0.6% depending on the nucleus involved, although there is some (small) scatter between the two calculations. A detailed discussion of all corrections can be found in Towner and Hardy (2002). Further, on the right hand side of Eq. (85) one has the constants

$$\frac{K}{(\hbar c)^6} = \frac{2\pi^3\hbar\ln 2}{(m_e c^2)^5} = 8120.271(12)\times 10^{-10}\,\mathrm{GeV}^{-4}\,\mathrm{s} \quad (87)$$

and

$$\frac{G_F}{(\hbar c)^3} = 1.16639(1)\times 10^{-5}\,\mathrm{GeV}^{-2}\,. \quad (88)$$

The value for the Fermi coupling constant G_F is known from the purely leptonic decay of the muon (Eidelman *et al.*, 2004). It is related by CVC (Sec. II.G) to the vector coupling constant G_V in nuclear beta-decay, $G_V = V_{ud}\,G_F\,g_V(q^2\to 0)$, with g_V the vector form factor and $g_V(q^2\to 0)=1$ the vector coupling constant with q the momentum transfer to the leptons in the decay.

According to the CVC hypothesis (Feynman and Gell-Mann, 1958) the $\mathcal{F}t$ value should be the same for all superallowed $0^+\to 0^+$ transitions. The fit to a constant of the corrected $\mathcal{F}t$ values for the twelve transitions yields $\mathcal{F}t = 3072.7(8)$ s (Hardy and Towner, 2005b) (Fig. 10), confirming the CVC hypothesis at the 3×10^{-4} precision level. Taking into account an additional error related to the above mentioned systematic difference between the two calculations of δ_c by Towner and Hardy (2002) and Ormand and Brown (1995) one gets $\mathcal{F}t = 3073.5(12)$ s (Hardy and Towner, 2005b) which leads to

$$|V_{ud}| = 0.9738(4) \quad \text{(superallowed transitions)} \quad (89)$$

2. Neutron decay

The matrix element $|V_{ud}|$ can also be determined from the decay of the free neutron. The ft-value for the neutron is given by

$$f_n\,\tau_n\,(1+\delta_R) = \frac{K\,/\,\ln 2}{G_F^2\,V_{ud}^2\,(1+\Delta_R^V)\,(1+3\lambda^2)} \quad (90)$$

with τ_n the lifetime of the free neutron and $f_n(1+\delta_R) = 1.71489(2)$ the phase space factor (Towner and Hardy, 1995; Wilkinson, 1982). The factor λ is the ratio of the effective vector and axial vector weak coupling constants, $\lambda = G'_A/G'_V$, with $G'^2_A = G_A^2(1+\Delta_R^A)$ and $G'^2_V = G_V^2(1+\Delta_R^V)$. Here, $G_A = V_{ud}\,G_F\,g_A(q^2\to 0)$, with g_A the axial vector form factor and $g_A(q^2\to 0)\approx -1.27$ the axial vector coupling constant. The factors Δ_R^A and Δ_R^V are the nucleus-independent radiative corrections. Since the neutron is a single nucleon, no nuclear structure correction δ_{NS} or isospin symmetry-breaking correction δ_C have to be applied (see also García *et al.*, 2001). However, one now has to determine the ratio λ which enters because the decay of the neutron proceeds through a mixed Fermi/Gamow-Teller transition. This is usually obtained in measurements of the beta asymmetry parameter A. Eq. (90) can be rewritten to obtain $|V_{ud}|$ as

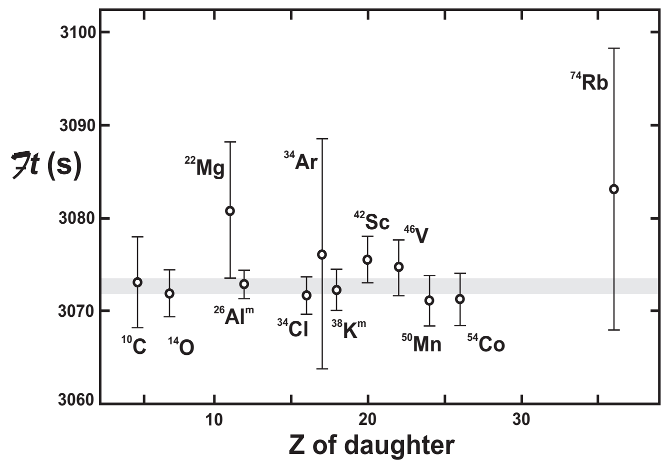

FIG. 10 $\mathcal{F}$t values for the superallowed $0^+\to 0^+$ transitions. The shaded band is the 1σ result from the best least-squares one-parameter fit. From Hardy and Towner (2005a).

$$|V_{ud}|^2 = \frac{4903.7(38)}{\tau_n(1+3\lambda^2)}. \quad (91)$$

The world average value for λ recommended by the Particle Data Group (Eidelman *et al.*, 2004) is

$$\lambda = -1.2695(29), \quad (92)$$

which is extracted mainly from measurements of the β asymmetry parameter (Fig. 11). The value for the neutron lifetime recommended by the Particle Data Group is

$$\tau_n = 885.7 \pm 0.8\ s, \quad (93)$$

which is the weighted average (with $\chi^2/\nu = 0.76$) of seven independent results (Fig. 12). It is dominated, however, by the value reported by Arzumanov *et al.* (2000). Recently, a new measurement of the neutron lifetime was reported (Serebrov *et al.*, 2005a). The result, $\tau_n = (878.5 \pm 0.7_{stat} \pm 0.3_{syst})$ s, although being obtained with a method rather similar to the one used by Arzumanov *et al.* (2000), differs by 6.5 standard deviations from the former world average. As a consequence, the data set for τ_n (Fig. 12) is now dominated by two very precise but conflicting results (see Fig. 12). In Sec.III it was shown that including the result of Serebrov *et al.* (2005a) worsens the χ^2/ν for the multi-parameter fits to the various couplings by a factor of about 2 to 3. The same is true here, i.e. combining all neutron lifetime data leads to a world average $\tau_n = (882.0 \pm 1.1)$ s with $\chi^2/\nu = 1.90$ (the uncertainty was increased accordingly). We therefore adopt the same approach with respect to this result as in Sec.III. Using then the world average neutron lifetime τ_n not including the most recent measurement, and the adopted value for λ, Eq. (91) yields

$$|V_{ud}| = 0.9741(20) \quad \text{(neutron decay)} \tag{94}$$

which agrees with the value obtained from the superallowed Fermi transitions but is a factor five less precise.

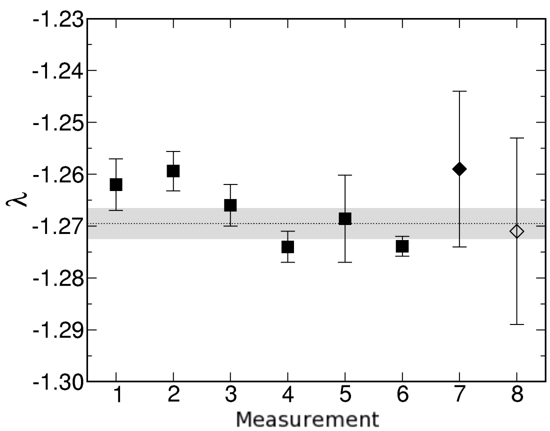

FIG. 11 Input data for the world average value of λ from measurements in neutron decay (See also Table IV). The most precise results are from measurements of the β asymmetry parameter A (1: Bopp *et al.*, 1986; 2: Yerozolimsky *et al.*, 1997; 3: Liaud *et al.*, 1997; 4: Abele *et al.*, 1997; 6: Abele *et al.*, 2002). Data points 7 (Stratowa *et al.*, 1978) and 8 (Byrne *et al.*, 2002) refer to measurements of the $\beta - \nu$ correlation coefficient a and data point 5 (Mostovoi *et al.*, 2001) is from a simultaneous measurement of the β asymmetry and the ν asymmetry parameters A and B. The band indicates the weighted average adopted by the Particle Data Group (Eidelman *et al.*, 2004).

3. Pion beta decay

The value of $|V_{ud}|$ can also be obtained from pion beta decay, $\pi^+ \rightarrow \pi^0\, e^+\, \nu_e$ (see e.g Towner and Hardy, 1999). As this is a $0^- \rightarrow 0^-$ pure vector transition, no separation of vector and axial-vector components is required. In addition, like neutron decay, it has the advantage that no nuclear structure-dependent corrections have to be applied. A major disadvantage, however, is that pion beta decay has a very weak branch, of the order of 10^{-8}, leading to severe experimental difficulties. The values for the

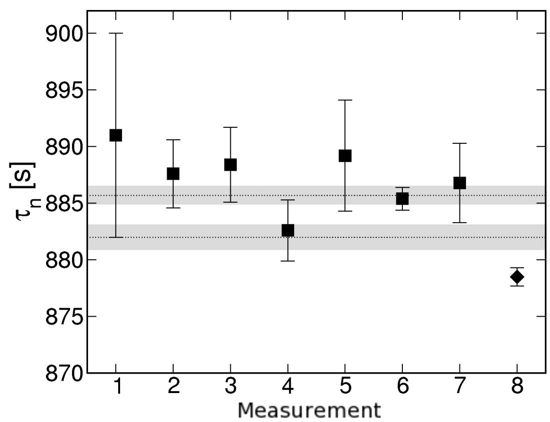

FIG. 12 Input data for the world average value of τ_n (See also Table IV). 1: Spivak, 1988; 2: Mampe *et al.*, 1989; 3: Nesvishevsky *et al.*, 1992; 4: Mampe *et al.*, 1993; 5: Byrne *et al.*, 1996; 6: Arzumanov *et al.*, 2000, 7: Dewey *et al.*, 2003 and 8: Serebrov *et al.*, 2005a. The upper band shows the weighted average of the first seven values and the lower band the weighted average of all values.

lifetime and branching given by the Particle Data Group (Eidelman *et al.*, 2004), are $\tau_\pi = (2.6033 \pm 0.0005) \times 10^{-8}$ s and $BR = 1.025(34) \times 10^{-8}$. Since the precision of this branching ratio is about an order of magnitude worse than the theoretical uncertainties, a new experiment was performed at the Paul Scherrer Institute. The analysis has yielded $BR = (1.036 \pm 0.004_{stat} \pm 0.005_{syst}) \times 10^{-8}$ (Pocanic *et al.*, 2004), corresponding to

$$|V_{ud}| = 0.9728(30) \quad \text{(pion } \beta \text{ decay).} \tag{95}$$

This is in agreement with but still much less precise than the value obtained from the superallowed Fermi β decays.

4. Status of unitarity

The values obtained for V_{ud} from the superallowed Fermi decays, from neutron decay and from pion β decay are compared to each other in Fig. 13. The values for the two other matrix elements in the first row that are recommended by the Particle Data Group are $|V_{us}|$ = 0.2200(26) and $|V_{ub}|$ = 0.00367(47) (Eidelman *et al.*, 2004). Note that the V_{ub} matrix element is so small that it does not contribute to the unitarity test at the present level of precision. As a consequence, since this test of unitarity is not even sensitive to the third quark generation, it will not be sensitive to a possible fourth generation either, except in some non-hierarchical scenarios where the couplings of fourth generation quarks would be larger than those of the third generation.

The third column of Table VI lists the results of the unitarity test when the values for $|V_{ud}|$ obtained from the three different types of β decay are combined with the current Particle Data Group value for $|V_{us}|$. For the su-

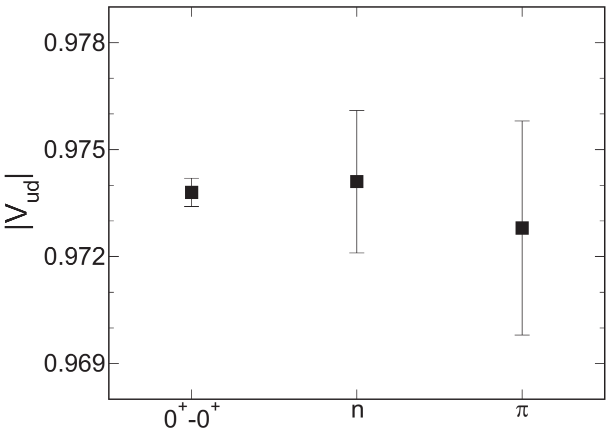

FIG. 13 Values for $|V_{ud}|$ obtained from the average $\mathcal{F}t$ value for the $0^+ \rightarrow 0^+$ superallowed Fermi β decays (Hardy and Towner, 2005b), from neutron decay (see text) and from pion β decay (Pocanic *et al.*, 2004).

perallowed Fermi decays a 2.5σ deviation from the standard model is observed. The current data for the decay of the neutron and for pion β decay are in agreement with unitarity but the error bars are a factor of three to five larger than is the case for the superallowed Fermi transitions.

decay	$\|V_{ud}\|$	$\|V_{us}\|$=0.2200(23)	$\|V_{us}\|$=0.2254(21)[1]
$0^+ \rightarrow 0^+$	0.9738(4)	0.9967(13)	0.9991(12)
neutron	0.9741(20)[2]	0.9973(40)	0.9997(40)
pion	0.9728(30)	0.9946(59)	0.9971(59)

TABLE VI Results of the unitarity test for the first row of the CKM matrix when combining the values of $|V_{ud}|$ obtained from $0^+ \rightarrow 0^+$ superallowed nuclear decays, from neutron decay and from pion beta decay (second column) with the value for $|V_{us}|$ adopted by the Particle Data Group (Eidelman *et al.*, 2004) (third column). The results of the unitarity test when the weighted average for $|V_{us}|$ from the recent results obtained in kaon decays is used is shown in the fourth column (see also Table VII). In all cases $|V_{ub}| = 0.00367(47)$ (Eidelman *et al.*, 2004) was used. ([1]: see Table VII; [2]: see Sec. IV.A.2)

In the past years several new determinations of $|V_{us}|$ were reported, namely by the E865 experiment at Brookhaven National Laboratory (Sher *et al.*, 2003), the KTeV Collaboration at Fermilab (Alexopoulos *et al.*, 2004), the NA48 Collaboration at CERN (Lai *et al.*, 2004) and the KLOE Collaboration at Frascati (Ambrosino *et al.*, 2006a; Franzini, 2004). All experiments have determined $|V_{us}|f_+(0)$ from charged kaon and/or neutral kaon decays, with the form factor $f_+(0)$ taking into account $SU(3)$ breaking and isospin breaking effects. Leutwyler and Roos (1984) calculated

$$f_+(0) = f_+^{K^0\pi^-} = 0.961(8), \tag{96}$$

a value that was confirmed by lattice calculation (Becirevic *et al.*, 2005), while chiral perturbation theory yields values that are slightly larger, i.e. 0.974(11) to 0.981(10) (Bijnens and Talavera, 2003; Cirigliano *et al.*, 2004; Jamin *et al.*, 2004). In the case of charged kaons (E865 experiment) the correction factor is

$$\begin{aligned} f_+(0) &= f_+^{K^+\pi^0} \simeq 1.022 f_+^{K^0\pi^-} \\ &= 0.982 \pm 0.008 \pm 0.002, \end{aligned} \tag{97}$$

due to $\pi - \eta$ mixing induced by $m_d - m_u$ mass splittings (Czarnecki *et al.*, 2004). An overview of the results for $|V_{us}|$ obtained from these new measurements is given in Table VII.

Experiment	Decay	$\|V_{us}\|f_+(0)$ [1]	$\|V_{us}\|$ [2]
E865	$K^+, e3$	0.2243(22)(7)[3]	0.2284(23)(20)
KTeV	$K_L, e3, \mu 3$	0.2165(12)[4]	0.2253(13)(20)
NA48	$K_L, e3$	0.2146(16)[5]	0.2233(17)(20)
KLOE[6]	$K_L, e3, \mu 3$	0.21673(59)	0.2255(6)(20)[7]
weighted average			0.2254(21)

TABLE VII Results for $|V_{us}|$ obtained from the recent measurements of $|V_{us}|f_+(0)$ in neutral and charged kaon decays. ([1]: for K$^+$ decay $f_+(0)$=0.982(8), while for K$_L$ decay $f_+(0)$=0.961(8) (see text); [2]: the first error is due to experimental uncertainties; the common error of 0.0020 is related to the uncertainty of $f_+(0)$; [3]: Sher *et al.* (2003); [4]: Alexopoulos *et al.* (2004); [5]: Lai *et al.* (2004); [6]: a result obtained at KLOE for the $K_S, e3$ decay is not included here as only a preliminary value, i.e. $|V_{us}| = 0.2254(17)$ (Franzini, 2004), is available to date; [7]: Ambrosino *et al.* (2006a)).

All values are in good agreement with each other leading to the weighted average

$$|V_{us}| = 0.2254(21) \quad \text{(kaon decays)}. \tag{98}$$

The central value is obtained as the weighted average using only the first error in Table VII. The error is the quadrature of 0.0020, from $f_+(0)$, and 0.0005 from experiment, and is thus dominated by the $f_+(0)$ calculations. This new value for V_{us} is 2.6σ larger than the value recommended by the Particle Data Group (Eidelman *et al.*, 2004). Combining this with the values of V_{ud} leads to perfect agreement with unitarity as can be seen in the last column of Table VI.

$|V_{us}|$ can also be extracted from hyperon β decay data. It is interesting to note that the new values for $|V_{us}|$ from kaon decays are in good agreement with the value $|V_{us}| = 0.2258(27)$ that was previously obtained from the analysis of semi-leptonic hyperon decays (García, Huerta, and Kielanowski, 1992). However, the

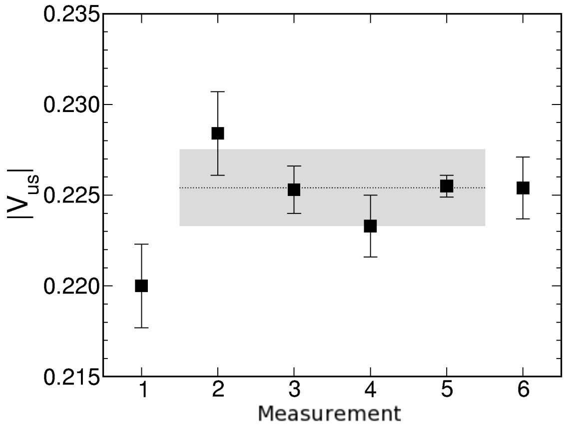

FIG. 14 Values for $|V_{us}|$ from the Particle Data Group analysis (1: Eidelman *et al.*, 2004) and from recent results in K decays (2: Sher *et al.*, 2003, 3: Alexopoulos *et al.*, 2004, 4: Lai *et al.*, 2004, 5: Ambrosino *et al.*, 2006a, 6:preliminary result from KLOE Franzini, 2004). The shaded band indicates the weighted average of the published new results from K-decays (refs. 2 - 5). See also Table VII.

analysis leading to this result has theoretical uncertainties because of first-order $SU(3)$ symmetry-breaking effects in the axial-vector couplings. Cabibbo *et al.* (2003) have therefore reanalyzed the hyperon β decay data using a technique that is not subject to these effects by focusing the analysis on the vector from factors. They obtained $|V_{us}| = 0.2250(27)$, again in good agreement with the new values from kaon decays (Table VII, Fig. 14).

Recent experimental results on hadronic τ decays into strange particles obtained by the OPAL Collaboration (Gámiz *et al.*, 2005), yielded V_{us}= 0.2208(34). This is somewhat lower than the values from kaon decays but, within the error bar, still in agreement with these. The error is dominated by experiment and should be improvable in the future. The main complications in this type of analysis are discussed by Maltman (2005).

Further, Marciano (2004) showed that combining the ratio of the experimental kaon and pion decay widths

$$\frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} \tag{99}$$

with lattice gauge theory calculations of the ratio f_K/f_π of the kaon and pion decay constants and the value $|V_{ud}|$ from superallowed β-decays, provides a precise value for $|V_{us}|$. Using

$$f_K/f_\pi = 1.120(4)(13) \tag{100}$$

from Aubin *et al.* (2004), Marciano (2004) found

$$|V_{us}| = 0.2219(25) \quad \text{(lattice 1)}, \tag{101}$$

while the value

$$f_K/f_\pi = 1.198(3)(^{16}_{-5}) \tag{102}$$

of Bernard *et al.* (2005) leads to

$$|V_{us}| = 0.2241(25) \quad \text{(lattice 2)}. \tag{103}$$

Although both values agree with Eq. 98 they still differ by about 1σ. Since, in addition, the accuracy on $|V_{us}|$ is in both cases dominated by the error on f_K/f_π, further improvements in the lattice determination of this ratio would be desirable. A reduction of the combined error on f_K/f_π by a factor of 2 to 4 may indeed be possible (Marciano, 2004). It is finally to be noted that the absolute branching ratio for the $K^+ \to \mu^+\nu(\gamma)$ decay was recently remeasured with the KLOE detector (Ambrosino *et al.*, 2006b). The result is in agreement but slightly more precise than the value adopted by the Particle Data Group (Eidelman *et al.*, 2004) that was used by Marciano (2004) to calculate $\Gamma(K \to \mu\nu(\gamma))/\Gamma(\pi \to \mu\nu(\gamma))$ (Eq. 99).

Combining now the weighted average value from the three types of β decay, *i.e.* $|V_{ud}| = 0.9738(4)$ (note that this is identical to the value from the superallowed Fermi decays) with the weighted average $|V_{us}| = 0.2254(21)$ from the recent measurements in kaon decays, yields for the current test of unitarity

$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9991(12)\,, \tag{104}$$

showing no sign for physics beyond the standard model at the present level of precision.

Finally, it is to be noted that the values of $f_+(0) = f_+^{K^0\pi^-} \simeq 0.974$ - 0.981 obtained from chiral perturbation theory (Bijnens and Talavera, 2003; Cirigliano *et al.*, 2004; Jamin *et al.*, 2004) result in a significantly lower weighted average in the last column of Table VII, i.e. $|V_{us}|$= 0.2208(21) - 0.2224(21), leading to

$$\sum_i V_{ui}^2 = V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9970(12) - 0.9977(12)\,, \tag{105}$$

which again deviates by 1.9σ to 2.5σ from unitarity. Resolving this ambiguity in the value of $f_+(0)$ should therefore be vigorously pursued. Marciano (2004) has pointed out that improvements in this respect may be expected from lattice gauge theory calculations.

Depending on the outcome of new and more precise calculations of the factor $f_+(0)$ in kaon decay the long standing so-called "unitarity problem"(Towner and Hardy, 2003) (see below) may finally be solved. However, because of its impact on the result of the unitarity test, the issue of the value of V_{us} should be definitely settled.

Since the precision on $|V_{ud}|$ from neutron decay is still well below what is presently obtained for the superallowed $0^+ \to 0^+$ transitions, new experiments in neutron decay are important too. The value of $|V_{ud}|$ from neutron decay is statistics limited and there is still room for improvement with the present experimental techniques. The same holds for pion beta decay.

Over the last decades significant progress was made in improving the precision and reliability of the experimental input data for the $0^+ \rightarrow 0^+$ transitions and for neutron decay, but also in calculating the corrections that have been described above. In a recent critical analysis (Towner and Hardy, 2003), prior to the new results for V_{us}, it was pointed out that if only the data for the $0^+ \rightarrow 0^+$ transitions are at variance with unitarity this could be due to a non-perfect understanding of the nuclear structure dependent corrections δ_{NS} and δ_C since these are absent in neutron decay. If the data for both the $0^+ \rightarrow 0^+$ transitions and neutron decay are at variance with unitarity this might be due to a non-perfect knowledge of the nucleus independent but model dependent radiative correction Δ_R^V. As long as the new value for V_{us} is not firmly established it would be useful to address both types of corrections in detail again. Whereas both the neutron and the pion results are still statistics limited, the dominant contribution to the precision of $|V_{ud}|$ obtained from the $0^+ \rightarrow 0^+$ nuclear decays comes from Δ_R^V, which is responsible for most of the uncertainty of the result $|V_{ud}| = 0.9738(4)$ (Hardy and Towner, 2005a,b). It is interesting to note that a new calculation of Δ_R^V by Marciano and Sirlin (2006) reduces the error on this radiative correction by a factor of 2, leading to

$$|V_{ud}| = 0.97377(27). \tag{106}$$

for the data listed by Hardy and Towner (2005b). Finally, since Δ_R^V also contributes to neutron decay experiments, neutron decay would be able to test whether there are important systematic problems with the nucleus-dependent corrections (δ_C and δ_{NS}) but cannot test unitarity with a significantly better precision than the nuclear decays.

If the new value $|V_{us}| = 0.2251(21)$ is confirmed, unitarity is validated at the 10^{-3} precision level for the $0^+ \rightarrow 0^+$ transitions and this then permits to set stringent limits on different types of new physics (see Sec. IV.B and Sec. IV.C).

5. Prospects for superallowed Fermi transitions

A number of precision nuclear spectroscopy experiments are ongoing or planned to check the nuclear structure dependent corrections for the $0^+ \rightarrow 0^+$ superallowed Fermi transitions. The total nuclear structure dependent correction $(\delta_C - \delta_{NS})$ is the second largest contribution to the error budget on $|V_{ud}|$ (Towner and Hardy, 2003). These corrections have been validated only to about 10% of their values, which range from 0.25 to 0.77% for the eight transitions that are currently best known. In order to improve on this, the available data set for the $0^+ \rightarrow 0^+$ transitions is now being significantly extended. New technical developments such as improved detection techniques at isotope separators and recoil separators, Penning traps for precision mass and Q-value measurements and improved production techniques for exotic isotopes permit precision measurements on several new $0^+ \rightarrow 0^+$ transitions of $T_z = -1$ nuclei with $18 < A < 42$ like ^{18}Ne, ^{22}Mg, ^{26}Si, ^{30}S, ^{34}Ar, ^{38}Ca and ^{42}Ti, as well as on a number of $0^+ \rightarrow 0^+$ transitions in the decay of $T_z = 0$ nuclei with $A > 54$ like ^{62}Ga, ^{66}As, ^{70}Br and ^{74}Rb (Hardy and Towner, 2005a). With the first group of transitions the present range of values for the total nuclear structure dependent correction $(\delta_C - \delta_{NS})$ will be extended from 0.77% to 1.12%. For the second group this correction has values between 1.4 and 1.5% (Hardy and Towner, 2002). The aim is to determine the ft-values for these transitions, which cover a wide range of calculated values for $(\delta_C - \delta_{NS})$, with a precision that is comparable to the present set of the eight best-known transitions. If the $\mathcal{F}t$-values that will be obtained after applying the calculated corrections are in agreement with CVC, this will verify the calculated corrections and act to reduce the uncertainty attributed to them, which are currently based only on theoretical estimates. If not, this will point to some other problem to be investigated in detail. First data are already available for most of the nuclei mentioned above (Hardy and Towner, 2005a). For ^{22}Mg, ^{34}Ar and ^{74}Rb results are sufficiently precise that they were included in the latest analysis of the $0^+ \rightarrow 0^+$ transitions (Hardy and Towner, 2005b). Further, in the case of ^{74}Rb a first experimental result has been obtained for the isospin-symmetry-breaking correction $\delta_C = 1.81(29)\%$ (Kellerbauer *et al.*, 2004) which is in good agreement with the theoretical value of 1.50(40)% (Towner and Hardy, 2003).

Finally, a new determination of the Q-value of the superallowed decay of ^{46}V obtained from the masses of both ^{46}V and its decay daughter ^{46}Ti, together with an investigation of an earlier Q-value measurement of ^{46}V has uncovered a set of 7 measurements that cannot be reconciled with modern data (Savard *et al.*, 2005). An analysis of the data used by Hardy and Towner (2005b) taking into account the new Q-value for ^{46}V and neglecting those 7 measurements leads to a shift of the average $\mathcal{F}t$ value for the superallowed $0^+ \rightarrow 0^+$ transitions of about 1σ (Savard *et al.*, 2005). Given the high precision that is now routinely available in Penning trap based mass measurements it would thus be desirable that the Q-values for all these transitions be determined again.

6. Experiments in neutron decay

In neutron decay new measurements of the lifetime and of several correlation coefficients (*viz.* the β asymmetry parameter A and the $\beta - \nu$ correlation coefficient a) are ongoing and planned, which should lead to a reduction of the error on V_{ud}. All experiments use cold, very cold and even ultra-cold neutrons (UCN). Cold neutrons have energies in the range $0.1 - 5$ meV, corresponding to wavelengths of $4 - 29$ Åand velocities of $140 - 1000$ m/s. UCN have energies of only $\sim 10^{-7}$ eV, corresponding to wavelengths of ~ 900 Åand velocities of ~ 5 m/s so that they move extremely slowly. Neutrons as slow as possible are required for these measurements since in many experiments the neutron decay is measured during its motion through an experimental set-up. It is then desirable that the neutron spends as much time as possible in the set-up as the slower it moves, the greater the probability that it will decay inside the set-up.

Most neutron decay experiments obtain their neutrons from nuclear reactors and spallation sources containing a moderator. The energy spectrum of the neutrons produced at the different facilities contains very few cold to UCN, the fraction of UCN amounting typically to $\sim 10^{-11}$ only. Cold neutrons are formed in the rare process in which a thermal neutron looses almost all of its energy in a single inelastic collision. The number of cold neutrons can be increased by passing the beam of thermal neutrons through an extra moderator, *e.g.* a container with liquid deuterium ($T \approx 23 - 25$ K). The neutrons then reach a new thermal equilibrium at the temperature of liquid deuterium, so that the maximum of the Maxwellian spectrum is shifted to the energy range of cold neutrons. The increase of the fraction of very cold and UCN in this way requires very low temperatures for the extra moderator ($\sim 10^{-3}$ K for UCN) which causes practical difficulties. However, with current techniques (see below) neutrons can now be stopped completely and be stored for a time typically as long as their lifetime in a certain volume such that one can simply wait for their decay. This resulted in an enormous gain in measurement efficiency because the neutron loss rate (which is the main limitation in lifetime measurements with cold neutrons) as well as other sources of systematic errors are significantly reduced.

At the current level of precision most techniques using cold neutrons for lifetime experiments have reached their systematic limits, such that significant progress in precision can only be made when UCN are used. Lifetime experiments at present-day UCN sources have provided values for the neutron lifetime which are a few times more precise than those from beam experiments (see *e.g.* Arzumanov *et al.*, 2000; Serebrov *et al.*, 2005a and Fig. 12). The UCN have too low energy to penetrate the surface of a material and therefore undergo total external reflection at all angles. The probability to be absorbed on each bounce has been measured to be of the order of less than one in ten thousand in several materials. UCN can therefore be stored for several hundreds of seconds (Huffman *et al.*, 2000a), and can also be guided through pipes with sharp bends. All this enables experiments with UCN to be shielded from the production source of the neutrons, both by physical shielding (since the neutrons can be guided around the shielding material) and by time (as one can store the neutrons until the background caused by their production has died away). If UCN are also used for measurements of correlations between the neutron spin and the momenta of the leptons emitted in free neutron decay a further increase in precision can be expected here too. Several such experiments are under preparation (see *e.g.* Carr *et al.*, 2000).

a. Neutron lifetime

Since the neutron decays via a mixed transition, any correlation experiment in neutron decay has to be combined with the neutron lifetime in order to fix the mixing ratio λ (Sec. IV.A.2). To determine the neutron lifetime both beam and storage experiments are used. In the first case decays from a neutron beam passing through an apparatus are observed, while in the second neutrons are stored for a while in a volume inside the apparatus and the remaining neutrons are counted.

At NIST a measurement was recently performed with the set-up shown in Fig. 15. In this type of beam experiment (Dewey *et al.*, 2003) one measures simultaneously both the number N of neutrons in a well-defined volume of a neutron beam and the number of neutron decays dN/dt in the same volume. The lifetime is then determined from the ratio $\tau_n = N/(dN/dt)$. The number of decays is obtained by trapping the protons from neutron decay in a cylindrical Penning trap and sending them at regular intervals onto a detector for counting (Byrne *et al.*, 1996, 1990). The number of neutrons that are present in the decay volume is determined by counting the number of α-particles or tritons emitted from the prompt decay of ^{7}Li after neutron capture on a well characterized isotopic target of ^{6}LiF. The resulting value, $\tau_n = (886.6 \pm 1.2_{stat} \pm 3.2_{syst})$ s (Dewey *et al.*, 2003; Nico *et al.*, 2005), is the most precise measurement of the neutron lifetime to date using an in-beam method. The error is dominated by systematics which is mainly caused by uncertainties in the mass of the (LiF)-^{6}Li deposit and the neutron capture ^{6}Li(n,t) cross section. Continuing efforts to measure the neutron count rate are underway by both calorimetric and coincidence techniques, which should reduce the present uncertainty by about a factor of two.

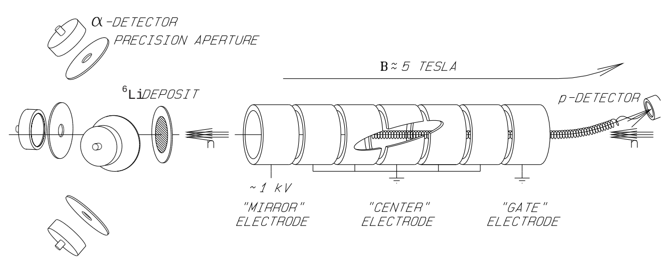

FIG. 15 Schematic drawing of the NIST Penning trap neutron lifetime experiment. Details are given in the text. From Dewey (2003).

The second strategy for measuring the neutron decay rate is based on the storage of UCN. The storage volume is defined either by material surfaces, by gravity or by the interaction of the neutron magnetic moment with a magnetic field gradient. Conceptually these experiments are rather simple. UCN are first injected and trapped in a storage volume with suitable walls, the "bottle". After a certain storage period the bottle is emptied and the number of surviving neutrons, $N(t)$, is measured. Repeating this experiment with different storage times yields the decay curve of the neutrons $N(t) = N(0)\exp(-t/\tau_n)$ which is then fitted to extract the lifetime τ_n. Special care has to be taken to correct for leakage, mainly due to absorption and inelastic scattering on the walls of the bottle. The total probability of neutron losses in the storage volume, $P_s = 1/\tau_s$, is determined by the sum of the probability of the neutron decay, $P_n = 1/\tau_n$, and the probability of leakage, $P_l = 1/\tau_l$, *viz.* $1/\tau_s = 1/\tau_n + 1/\tau_l$. Several methods are used to separate the different loss mechanisms (Mampe *et al.*, 1989; Nesvishevsky *et al.*, 1992). Two experiments were recently performed at the ILL with the walls of the storage bottle being coated with a film of hydrogen-free Fomblin oil. In the first the neutrons were trapped in a material bottle with variable volume and Fomblin oil at ∼250 K, yielding $\tau_n = (885.4 \pm 0.9_{stat} \pm 0.4_{syst})$ s (Arzumanov *et al.*, 2000). The second experiment used low temperature Fomblin oil (at ∼110 K) so as to further reduce systematic errors (Serebrov *et al.*, 2005a). The result, $\tau_n = (878.5 \pm 0.7_{stat} \pm 0.3_{syst})$ s, surprisingly differs by 5.6σ from the previous result and by 6.5σ from the former world average value. It is interesting to note in this respect that a new experiment using a gravitational storage system with a wall coating of low temperature Fomblin oil (105 K to 150 K) is planned at ILL (Yerozolimsky *et al.*, 2005).

Recently, progress was made at NIST towards magnetic trapping of UCN (Huffman *et al.*, 2000a,b). Due to the magnetic moment of the neutron a magnetic field gradient will, depending on its orientation, either accelerate neutrons and let them pass, or retard them by creating a potential barrier without material substance. By using a magnetic field as a boundary to reflect neutrons, the problem of losses due to interactions with material walls can be avoided. Together with the reduction of several other systematic errors and a high yield this is expected to lead to significantly improved precision. The UCN are produced by inelastic scattering of cold (8.9 Å) neutrons with phonons in superfluid ^{4}He (at T<250 mK) and are confined in a three-dimensional magnetic trap using superconducting magnets. The electrons emitted by the trapped neutrons ionize helium atoms in the superfluid resulting in scintillation light pulses that are recorded with nearly 100% efficiency. The neutron lifetime can be directly determined from the scintillation rate as a function of time. A proof-of-principle of this technique has been demonstrated (Huffman *et al.*, 2000a). The apparatus is equipped with a larger magnet for a measurement of the neutron lifetime at the 10^{-3} level (Dewey, 2001). A further gain in precision by at least another order of magnitude is anticipated (Alonso, 1999; Gabriel, 2003) when combining this apparatus with a higher-flux cold neutron source, such as the Spallation Neutron Source (SNS) at the Oak Ridge National Laboratory.

The storage of UCN in a small magnetic trap made of permanent magnets was also demonstrated (Ezhov *et al.*, 2001, 2005). The measured storage time in a test measurement was (882 ± 16) s, with no depolarization being observed at this level of accuracy.

Another method that was suggested is to combine gravitational and magnetic forces for spatial confinement (so-called spin trap) (Zimmer, 2000).

b. Neutron β asymmetry parameter

Up to now the value of the mixing ratio λ was usually extracted from the β asymmetry parameter A. However, as the presently available results for λ are not in very good agreement (Fig. 11) new and more precise determinations of the A parameter are required.

The Heidelberg group has installed a ballistic supermirror neutron guide (Häse *et al.*, 2002) at the ILL. This delivers the presently best and most intense polarized neutron beam in the world, providing an increase of about a factor of 6 in the cold neutron flux, corresponding to 2×10^6 neutron decays per second and per meter of beam length. By using crossed super-mirror polarizers (Petoukhov *et al.*, 2003) a neutron polarization larger than 99.5 % is obtained over the full cross-section of the neutron beam (6×20 cm^2). The neutron polarization is determined with a new polarimeter which is based on spin-dependent neutron absorption in polarized ^{3}He and which yields a precision of about 0.1 % (Heil *et al.*, 1998; Zimmer *et al.*, 1999). Following these upgrades a new high-precision determination of the A-parameter is being prepared with the PERKEO-II set-up (Fig. 16) (Reich *et al.*, 2000). The magnitude of the main correction is expected to be reduced from 1.1% to less than 0.5% with an error of 0.1%, which would lead to precision of 0.1% or better on λ (Abele, 2003).

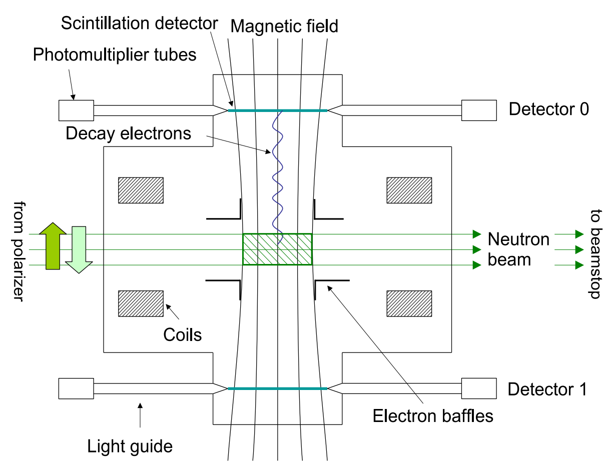

FIG. 16 Schematic view of the PERKEO-II spectrometer. The neutron beam passes through the apparatus. Electrons from neutron decays in the center of the chamber are focused by a strong magnetic field on two scintillator detectors. Adapted from Reich *et al.* (2000).

At LANSCE (Los Alamos) the UCNA collaboration has made progress toward measuring the electron asymmetry parameter A with neutrons from a spallation-driven solid deuterium UCN source (Carr *et al.*, 2000). The use of UCN in combination with a superconducting solenoidal spectrometer that ensures 4π coverage for the decay electrons, and a wire chamber/scintillator combination as electron detector will greatly suppress the backscattering of electrons at the surface of the detector (Young, 2001). The precision aimed for is at the level of 0.3% .

A group at PNPI (St.Petersburg, Russia) is preparing a new set-up to measure the A coefficient using cold neutrons and the axial magnetic field in the shape of a "bottle" provided by a superconducting magnet system (Serebrov *et al.*, 2005b). Such configuration permits to extract the decay electrons inside a small solid angle with high accuracy. Background will be suppressed by the use of electron-proton coincidences. An accuracy at the level of a few 10^{-3} is being pursued.

A simultaneous measurement of the coefficients A and B, eliminating the need to determine the neutron polarization with high precision, was carried out by Mostovoi *et al.* (2001), yielding a precision of 0.4% on λ.

The abBA collaboration (Bowman *et al.*, 2003; Wilburn *et al.*, 2001) prepares a detector that would be able to measure the correlations a, b, A, and B with a precision of approximately 10^{-4}, using a pulsed neutron beam at the SNS in Oak Ridge. The experiment uses an electromagnetic spectrometer combined with two large-area segmented Si detectors to detect the decay proton and electron in coincidence, with 4π acceptance for both particles. Measuring four correlation coefficients with the same apparatus enables a redundant determination of λ, with multiple cross checks on systematic effects.

Finally, at NIST an experiment is being set up to measure the so-called spin-proton asymmetry parameter, C, in polarized neutron decay (Dewey, 2001). This is proportional to $A + B$ and is related to λ via (Glück, 1996)

$$C \propto \lambda/(1 + 3\lambda^2). \tag{107}$$

In the proposed experiment (Fig. 17) longitudinally polarized neutrons will be guided into a 5 T solenoid and the decay protons, reflected by an electrostatic mirror, will then be counted with a silicon detector. The number of decay protons emitted parallel versus anti-parallel to the neutron polarization yields the proton asymmetry C. Polarized ^{3}He neutron spin filters will be used for high accuracy neutron polarimetry. A 0.5% measurement of λ is envisaged with this method.

It is to be noted that since experimental precisions below 1% are now possible for A (Abele, 2000), the inclusion of recoil-order effects and radiative corrections (García *et al.*, 2001; Gardner and Zhang, 2001; Glück, 1997, 1998; Holstein, 1974, 1976; Holstein *et al.*, 1972) in the interpretation of the experimental data has to be considered.

c. Beta-neutrino correlation in neutron decay

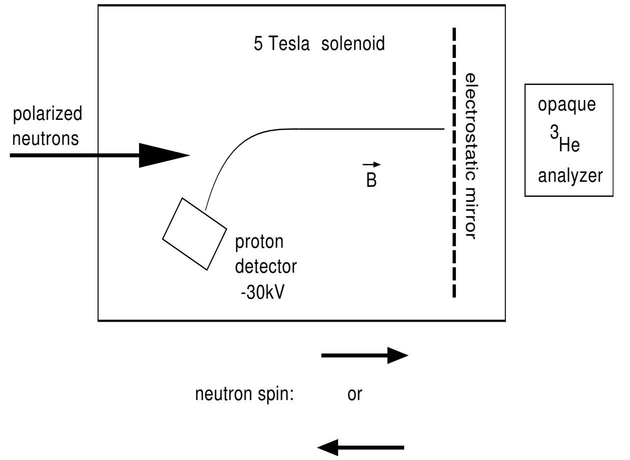

FIG. 17 Schematic of the proposed set-up to measure the spin-proton asymmetry coefficient C at NIST. Details are given in the text. From Dewey (2001).

A measurement of the beta-neutrino angular correlation coefficient a in neutron decay has a similar sensitivity to λ as the beta asymmetry parameter A. However, measurements of the correlation coefficient a are more difficult than measurements of the A parameter since the low energy (*viz.* < 751 eV) recoil protons have to be detected. Only a few precision measurements of this coefficient have been carried out (Byrne *et al.*, 2002; Grigoriev *et al.*, 1968; Stratowa *et al.*, 1978). The two most precise measurements, which yielded $a = -0.1017(51)$ (Stratowa *et al.*, 1978), and $a = -0.1054(55)$ (Byrne *et al.*, 2002), achieved a similar precision, corresponding to $\lambda = -1.259(15)$ and $\lambda = -1.271(18)$. Comparing these values with the present best result from a measurement of the asymmetry parameter A, *i.e.* $\lambda = -1.2739(19)$ (Abele *et al.*, 2002) (see also Fig. 11), it is clear that the precision in beta-neutrino correlation measurements has to be improved by almost an order of magnitude in order to be competitive with measurements of the A parameter. Note also that in view of the fact that the consistency of the results for the asymmetry parameter A is not very satisfactory (Fig. 11 and García *et al.*, 2001), it is important that measurements leading to an improved precision for a be pursued.

In the most recent measurement (Byrne *et al.*, 2002), a was deduced from the shape of the integrated energy spectrum of the recoil protons from the β decay of unpolarized neutrons.

In an experiment that is being prepared at NIST ("aCORN") (Dewey, 2001; Wietfeldt *et al.*, 2005) a new approach will be pursued. It relies on a coincidence measurement between the decay electron and the recoil proton and on the construction of an asymmetry that directly yields a without requiring precise proton spectroscopy. The electron energy and the time-of-flight between electron and proton detection will be measured.

A new spectrometer was designed for this. A statistical precision of less than 1 % on a is anticipated, while it is planned to control all expected systematic effects at the level of 0.5% or less.

Another method (Zimmer *et al.*, 2000) is based on a magnetic spectrometer with electrostatic retardation potentials. This spectrometer, called *a*spect, is currently being developed at Mainz and will be set up at the ILL. The main idea is to increase the precision by completely separating the source of decay protons from the spectroscopy part of the apparatus. The set-up is shown schematically in Fig. 18. The neutron beam passes through a region with a strong and rather homogeneous magnetic field B_0. Decay protons which have an initial momentum component towards the proton detector spiral along the field lines and reach a region with a weak magnetic field B_w. In an adiabatic motion, most of their initial kinetic energy perpendicular to the field is transformed into longitudinal kinetic energy, the exact fraction depending on the ratio B_w/B_0. In the weak field region an electrostatic potential U is applied for the energy selection of the arriving protons. Protons with total kinetic energy T can overcome this potential barrier only if their longitudinal energy is larger than U. A second region with strong magnetic field $B \simeq B_0$ is used for magnetic focusing of the protons onto the detector. Protons which had enough energy to overcome the potential barrier are post-accelerated in this region to a final energy of ~ 30 keV in order to obtain a measurable signal. Counting the number of protons as a function of the retardation potential U permits to measure the proton recoil energy spectrum which can be fitted to obtain the beta-neutrino correlation coefficient a. This experiment aims at a statistical error of about 2.5×10^{-3} and a systematic error of about $1 - 2 \times 10^{-3}$ (Zimmer *et al.*, 2000).

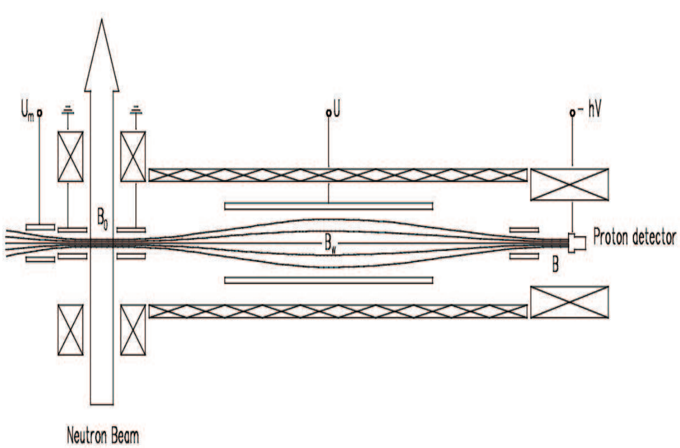

FIG. 18 Schematic of the *a*spect spectrometer. Details are given in the text. From Zimmer *et al.* (2000).

Finally, a new measurement of a is also planned at the UCN source at Los Alamos (Young, 2002) and at the SNS at Oak Ridge, as discussed above (Bowman *et al.*, 2003).

d. Rare neutron decay

Efforts are ongoing to observe for the first time the radiative decay mode of the free neutron. Whereas this decay branch is well investigated already for other particles no efforts were done as yet for the neutron. Recent theoretical calculations (Gaponov and Khafizov, 1996) estimate this contribution to be about 1.5% of the total neutron β decay probability and about 0.1% for the experimentally rather easily accessible energy region between 35 keV and 100 keV (above 100 keV the probability becomes negligible). Recently, an experiment at the ILL-Grenoble has yielded an upper limit of 6.9×10^{-3} (90% C.L.) for this energy region (Beck *et al.*, 2002). In this experiment the radiative decay mode is singled out by triple electron-proton-gamma coincidences, with electron-proton coincidences signaling a normal neutron β decay. To reduce correlated background events from bremsstrahlung emitted by the electron traveling through the detector, a sectioned electron-gamma detector is used with the six segments of the CsI gamma detector being placed at 35° with respect to the axis of the plastic scintillator electron detector. The experiment was recently moved to the new FRM-II reactor in München. In a first phase a precision of about 10% on the branching ratio is aimed at.

At NIST a neutron radiative decay experiment is being set up too (Dewey, 2001; Fisher *et al.*, 2005). This experiment will use the existing apparatus for the lifetime measurement mentioned above, which can provide substantial background reduction by using an electron-proton coincidence trigger.

Note that if the radiative decay mode of the neutron can be established, new correlations and polarization features in neutron decay may be studied, including additionally the momentum or the polarization of the radiative photon.

B. Exotic interactions

In addition to the observed V and A type interactions the general β decay Hamiltonian includes also scalar (S) and tensor (T) interactions, Eq. (7). At the tree level scalar type interactions in the $d \to ue^-\overline{\nu}_e$ decay can arise from the exchange of Higgs bosons and spin-zero or spin-one leptoquarks. In supersymmetric models with R-parity violation it can be due to the exchange of sleptons (Herczeg, 2001). They can appear also in so-called composite models in the form of contact interactions (Cornet and Rico, 1997; Herczeg, 2001; Zeppenfeld and Cheung, 1999). Tensor type interactions can arise from the exchange of spin-zero leptoquarks and as contact interactions in composite models (Herczeg, 2001).

Constraints on S- and T-couplings in β decay are usually obtained either from the Fierz interference term b or from the β-ν correlation coefficient a.

The Fierz interference term b depends linearly on the coupling constants. In the standard model with only V and A couplings, $b = 0$. A measurement of b yields a narrow unlimited band as constraint in the C_i versus $C_i^{'}$ (i= S or T) parameter plane. In addition, b is identically zero if the exotic couplings are purely right-handed ($C_i = -C_i^{'}$). Since the Fierz interference term does not depend on any particular spin or momentum vector it is an integral part of most measurements in β decay. It can easily be shown that in most correlation measurements the actual quantity that is determined experimentally is not X but

$$\widetilde{X} = \frac{X}{1 + \langle b' \rangle} \tag{108}$$

with $X = a, A, B, D, R$, etc., $b' \equiv (m/E_e)b$ and where $\langle\,\rangle$ stands for the weighted average over the observed part of the β spectrum.

The β-ν correlation coefficient a depends quadratically on the exotic couplings. A higher experimental precision is thus needed in this case in order to get the same absolute constraints on the couplings compared to measurements of the Fierz interference term. However, a measurement of a constrains a closed region in the parameter plane and is independent of the helicity properties of the different interaction types. Note that for a Fermi transition one has $a_F = +1$ for a pure V-interaction and $a_F = -1$ for a pure S-interaction, while for a Gamow-Teller transition $a_{GT} = -1/3$ for a pure A-interaction and $a_{GT} = +1/3$ for a pure T-interaction.

Recently, a comprehensive analysis of experimental data for the neutron lifetime and the correlation coefficients a, A and B in neutron decay was carried out (Mostovoi, Gaponov, and Yerozolimsky, 2000). The analysis assumed right-handed couplings for scalar and tensor interactions and yielded (68% C.L.) $|C_S^{(\prime)}/C_V| < 0.11$ and $|C_T^{(\prime)}/C_A| < 0.08$. Under the same assumptions the present analysis of the data set including results from both neutron and nuclear β decay experiments, yields (95.5% C.L.) (Sec. III.D.1, case 4) $|C_S/C_V| < 0.07$ and $|C_T/C_A| < 0.08$, while the most general fit of neutron and nuclear β decay data (Sec. III.E, case 6) yields (95.5% C.L.) $|C_S^{(\prime)}/C_V| < 0.07$ and $|C_T^{(\prime)}/C_A| < 0.09$.

Thus, 40 years after it was established that the weak interaction is dominated by V and A currents (Allen *et al.*, 1959), scalar and tensor interactions are ruled out only to the level of about 5 to 10% of the V- and A-interactions. The present constraints still allow to accommodate sizable contributions of scalar and tensor interactions without affecting our conclusions on the phenomenology of semi-leptonic weak processes.

1. Fierz interference term

Strong limits on exotic couplings were recently obtained from the Fierz interference term extracted from the $\mathcal{F}t$-value of the superallowed $0^+ \to 0^+$ transitions and from the so-called polarization asymmetry correlation.

Assuming a non-zero Fierz interference coefficient b, the $\mathcal{F}t$-value for the superallowed $0^+ \to 0^+$ transitions is written as

$$\mathcal{F}t = \frac{K}{2G_F^2 V_{ud}^2 (1 + \Delta_R^V)} \frac{1}{(1 + \langle b'_F \rangle)} \tag{109}$$

where b'_F is the Fermi part of the Fierz interference term defined in Eq. (C7)[5]. The latest analysis (Hardy and Towner, 2005b) has yielded $(C_S + C'_S)/C_V = -0.0001(26)$ (assuming maximal parity violation for the vector interaction), corresponding to $-0.0044 < (C_S + C'_S)/C_V < 0.0044$ (90% C.L.).

Strong limits for tensor couplings were previously obtained (Boothroyd, Markey, and Vogel, 1984) from a measurement of the b coefficient in the decay of ^{22}Na. However, these limits can be questioned because of the large logft-value for this beta transition such that effects of higher order matrix elements can be important.

More recently, limits for tensor couplings were obtained from the Fierz interference term in a so-called polarization asymmetry correlation experiment where the longitudinal polarization of positrons emitted by polarized ^{107}In nuclei (log$ft = 5.6$) was measured (see Sec. IV.C.3), yielding $-0.034 < (C_T + C'_T)/C_A < 0.005$ (90% C.L.) (Camps, 1997; Severijns *et al.*, 2000).

2. Beta-neutrino correlation

Since neutrinos are very hard to detect, the β-ν correlation in semi-leptonic processes is usually investigated by observing the β particle and/or the recoiling nucleus, taking into account the kinematics of the decay.

a. Indirect measurements of the recoiling nucleus

Macfarlane *et al.* (1971) and later Clifford *et al.* (1983, 1989) showed that the β-ν correlation can be obtained from the kinematic broadening of β delayed α particles. More recently, several experiments were carried out to determine the β-ν correlation from the Doppler shift of gamma rays following the β decay to an excited state of the daughter nucleus. For ^{18}Ne this yielded $a = 1.06 \pm 0.10$ (Egorov *et al.*, 1997). The precision was limited by a systematic error related to the effects of the slowing down of ^{18}Ne in the beryllium-oxide target. A similar measurement with ^{14}O did not yield a final result for a due to unexpected problems related to molecular binding effects (Vorobel *et al.*, 2003).

[5] Note that the factor $\gamma m/E_e$ which appears explicitly in a similar expression in Towner and Hardy (2003) has been included here in the definition of the Fierz interference term b'.

Schardt and Riisager (1993) measured the kinematic broadening of β delayed protons in the pure Fermi decay of ^{32}Ar and the mixed decay of ^{33}Ar. These measurements were repeated at ISOLDE-CERN with improved precision (Adelberger *et al.*, 1999; García *et al.*, 2000). The result for ^{32}Ar is compared with theoretical expectations for pure S- and V-interactions in Fig. 19. Fitting the shape of this delayed proton group yielded $\tilde{a} = 0.9989 \pm 0.0052_{stat} \pm 0.0039_{syst}$, improving the limits on a possible scalar contribution. The systematic error is mainly due to the adopted error on the mass of ^{32}Ar that was obtained from a fit of the Isobaric Multiplet Mass Equation. A direct mass measurement of ^{32}Ar was meanwhile performed at ISOLDE (Blaum *et al.*, 2003). The reanalysis of the above mentioned experiment, taking into account the measured mass of ^{32}Ar is in progress (García, 2003).

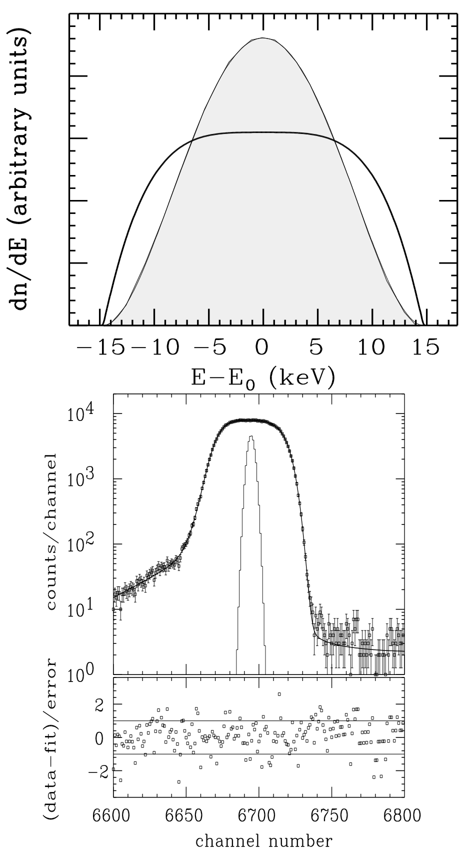

FIG. 19 Top: Shapes of the β delayed proton group from ^{32}Ar $0^+ \to 0^+$ decay for $a = +1, b = 0$ (pure V interaction; flat curve) and $a = -1, b = 0$ (pure S interaction; 'Gaussian'-like curve). Bottom: Fit (upper panel) and residuals (lower panel) of the proton peak (0.500 keV/channel). The narrow pulser peak in the upper panel shows the electronic resolution. From Adelberger *et al.* (1999).

b. Direct measurements of the recoil

The advent of ion and atom traps in nuclear physics has led to a new series of measurements of the β-ν correlation a and the β emission asymmetry parameter A (Behr, 2003; Kluge, 2002; Sprouse and Orozco, 1997). These tools enable β particles and recoil ions from β decay to be detected with minimal disturbance from scattering and slowing down effects.

The first successful application of an atom trap in a correlation measurement in nuclear β decay was the TRINAT experiment at TRIUMF (Gorelov *et al.*, 2000, 2005) which uses two Magneto Optical Traps (MOT) (Fig. 20) and is set up at the ISAC isotope separator. The possible presence of a scalar interaction was probed by investigating the β-ν correlation in the pure Fermi decay of ^{38m}K. The ^{38m}K ions were implanted in a Zr foil that was periodically heated in order to release the atoms which were then trapped in a first MOT. To avoid the large background from untrapped atoms, the trapped atoms were transferred to a second MOT by a laser push beam and 2-D magneto-optical funnels. A telescope detector for the β particles and a Z-stack of three micro channel plates to detect the recoil ions were installed in this second MOT. The recoil ion energy was determined by its time-of-flight with the β particle providing the start signal. Typical recoil time-of-flight spectra are shown in Fig. 20. The result $\tilde{a}$=0.9981$\pm$0.0030$^{+0.0032}_{-0.0037}$ (Gorelov *et al.*, 2005) is in agreement with the standard model.

At Berkeley a MOT was used to study the β-ν correlation in the mixed decay of the mirror nucleus ^{21}Na (Scielzo, 2003a; Scielzo *et al.*, 2004). As this transition is mainly (67%) of Fermi character, this experiment was predominantly sensitive to scalar currents. A ^{21}Na atomic beam was produced with a proton beam from the LBL 88" cyclotron. The ^{21}Na atoms were loaded into a MOT using a Zeeman slower. The correlation coefficient a was obtained from the time-of-flight spectrum of the recoiling ^{21}Ne ions from ^{21}Na β decays in the trap. The result, $a = 0.5243(92)$, differs by about 3σ from the value of 0.558(3) calculated within the standard model using the experimental ft-value (Naviliat-Cuncic *et al.*, 1991). This deviation could be caused by a systematic dependence of the result on the ion-trap population (Scielzo *et al.*, 2004). Another possible explanation for the discrepancy is the reliability of the ft-value. In particular, there is a several percent branch to an excited daughter state to be considered (Firestone, 1996). Several measurements of this branching ratio have been carried out but the consistency of the results is not satisfactory. It is planned to remeasure this branching ratio with better precision both at TRIUMF (Scielzo, 2003b) and at the KVI-Groningen (Achouri *et al.*, 2004).

Measurements of the β-ν correlation with radioactive isotopes (^{19}Ne, ^{20}Na and ^{21}Na) stored in a MOT atom trap are also planned at the new TRIμP facility at the KVI-Groningen (Berg *et al.*, 2003a,b). Here radioactive isotopes are produced in inverse-kinematics from fragmentation reactions initiated with heavy ions accelerated in the superconducting cyclotron AGOR. Reaction products are separated from the primary beam in a dual-mode recoil and fragment separator. Beams of isotopes of in-

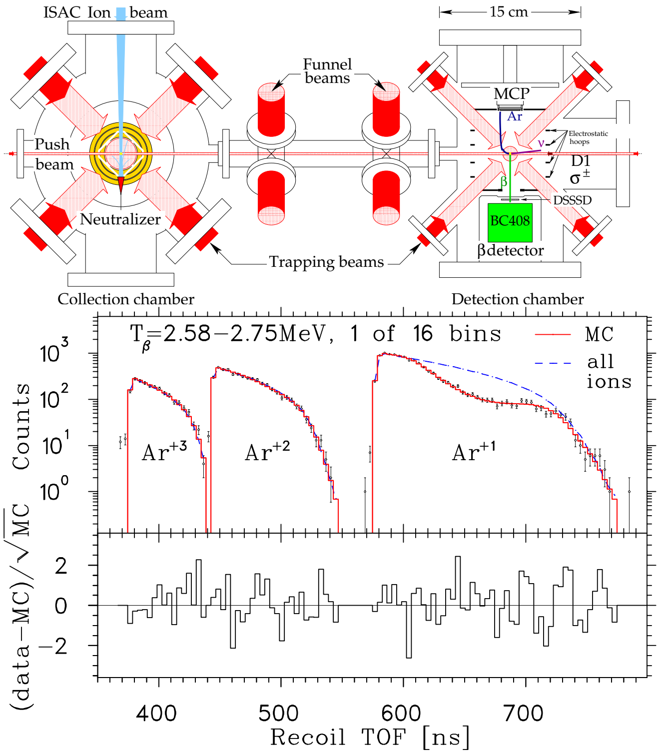

FIG. 20 Top: Top view of the TRINAT two-MOT apparatus. The ion beam is implanted in a neutralizer Zr foil in the trap at the left. Atoms that leave the foil after heating are trapped with six laser beams in three mutually perpendicular directions. At regular intervals the trapped atom cloud is transferred to the measurement trap at the right where the decay β particles and recoil ions are observed. The second MOT chamber is 15 cm in diameter. Bottom: Time-of-flight of Ar recoils from ^{38}K decay. Ar charge states are separated by a 800 V/cm field. From Gorelov *et al.* (2000; 2005).

terest will be transformed into a low-energy, high-quality, bunched beam and, after neutralization, stored in a MOT for measurement.

Experiments to measure the β-ν correlation using electromagnetic traps are being prepared too, one at GANIL (Ban *et al.*, 2005; Delahaye, 2002) and the other at ISOLDE-CERN (Beck *et al.*, 2003a,b).

The first experiment aims at determining the β-ν angular correlation in the decay of ^{6}He. This is a pure GT transition and is thus sensitive to tensor couplings. The goal is to improve the old experiment of Johnson *et al.* (1963) which determined a_{GT} with a relative precision of about 1%. The ^{6}He nuclei are produced by heavy ion reactions in the target/ion source system of the SPIRAL facility at GANIL. The ^{6}He$^+$ ions are extracted from the source with energies in the range 10-35 keV. The radioactive ion beam is then cooled and bunched in order to increase the injection efficiency of the ions into a Paul trap. The cooling and bunching is performed by a Radio Frequency Quadrupole using the buffer gas cooling technique (Darius *et al.*, 2004). The cooling of ^{4}He$^+$ ions using H_2 as buffer gas has very recently been demonstrated (Ban *et al.*, 2004), yielding transmissions of up to 10% which are enough to trap sufficient ions into the Paul trap. The trap (Fig. 21) has been designed with an open geometry to reduce the scattering of electrons on the electrodes while enabling the detection of the decay products. The quadrupole trapping field is generated by four concentric ring electrodes (Ban *et al.*, 2005) mounted around the beam axis. The β-ν correlation will be deduced from time of flight measurements between the β particles and the recoil ions. The β particles are detected by a telescope consisting of a 300 μm silicon strip detector (SSD) and a thick plastic scintillator while the recoiling ions are counted with a position sensitive micro-channel plate. An additional ion detector is mounted along the beam line to monitor the phase space of the trapped ions cloud. The set-up has been commissioned and the proof of principle has recently been demonstrated (Méry, 2005).

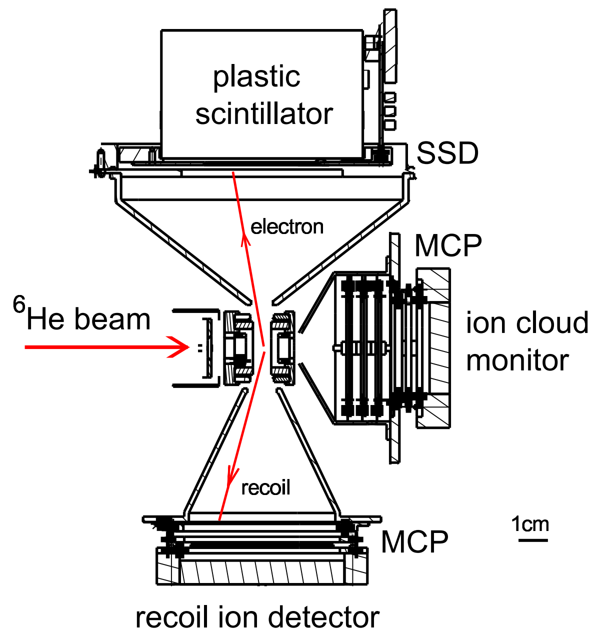

FIG. 21 Schematic lay-out of the LPC Caen transparent Paul trap set-up with the beta and recoil detectors, and the ion cloud monitor. The system is mounted on the low energy beam line of the SPIRAL facility at GANIL (see text for details).

The second set-up ("WITCH") is based on a magnetic spectrometer with electrostatic retardation potentials and was installed at ISOLDE-CERN. (Beck *et al.*, 2003a,b) (Fig. 22). A pulsed radioactive beam coming from the REXTRAP Penning trap at ISOLDE is slowed down in a pulsed drift tube and caught in a first (cooler) Penning trap situated in a 9 T magnetic field. The cooled ions are transferred to a second (decay) Penning trap where they are stored for some time. Recoil ions from decays in this second trap spiral adiabatically from the high magnetic field to a low magnetic field region (0.1 T) where a retardation potential is applied. While the ions travel from the high to the low field region most of their energy is converted into axial energy which is then probed by the retardation potential. This is the same principle which has been discussed already for the *a*spect experiment (Sec. IV.A.6) and that is used also for the direct neutrino mass measurements (Sec. IV.E.2). Recoil ions with longitudinal energy large enough to overcome the retardation potential are re-accelerated and electrostatically focused onto a micro-channel plate detector. The recoil energy spectrum, the shape of which depends on the β-ν correlation coefficient a, is then measured by scanning the retardation potential. The WITCH-experiment will first focus on ^{35}Ar. Since the Gamow-Teller component in the mirror β decay of ^{35}Ar is small (7%), this will thus mainly probe the existence of scalar weak currents. Eventually, also pure 0^+-0^+ transitions (^{26m}Ar) and pure Gamow-Teller transitions (^{122m}In) will be measured. The aim is to reach a precision on a of about 0.5 % or better.

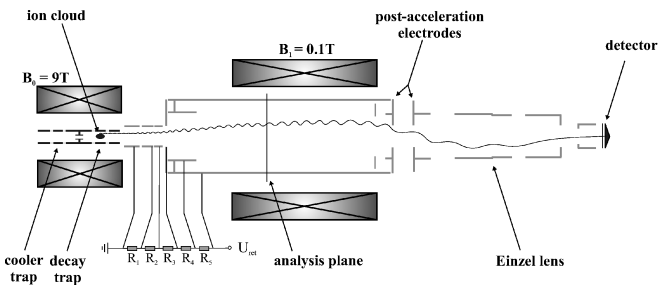

FIG. 22 Spectrometer section of the WITCH set-up. Details are given in the text. From Beck *et al.* (2003a).

Figure 23 shows the results of β-ν correlation measurements with a precision better than 10% available to date.

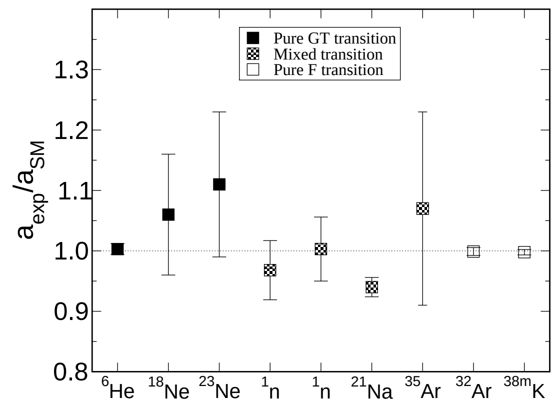

FIG. 23 Results of the early β-ν correlation measurements of Allen *et al.* (1959) for ^{23}Ne and ^{35}Ar, compared to more recent measurements. Only results with a precision better than 10% are included while, in addition, for a given isotope only the most precise result is shown. The about 3σ deviation from the standard model for ^{21}Na could be caused by a systematic dependence of the result on the ion-trap population, or by a problem with the value of the branching ratio that was used to calculate the ft-value (Scielzo *et al.*, 2004) (see text). (^{6}He: Johnson *et al.*, 1963; ^{18}Ne: Egorov *et al.*, 1997; ^{23}Ne: Allen *et al.*, 1959; n: Stratowa *et al.*, 1978 and Byrne *et al.*, 2002; ^{21}Na: Scielzo *et al.*, 2004; ^{35}Ar: Allen *et al.*, 1959; ^{32}Ar: Adelberger *et al.*, 1999; ^{38m}K: Gorelov *et al.*, 2005)

3. Beta-asymmetry parameter

The asymmetry parameter A in neutron decay is not very sensitive to the presence of either real scalar or tensor currents (see Eq. (C9)). Also for nuclear decays A is not sensitive to scalar currents as it vanishes for a pure Fermi transition. Over the years a number of measurements of A for T = 1/2 mirror transitions were carried out, mainly as a test of CVC (Table VIII and Fig. 24). Precision measurements of A for pure Gamow-Teller transitions, on the other hand, permit the existence of a tensor component in the weak interaction to be probed. Only a limited number of measurements of this type were carried out till now (Table V) and several of these results have a poor precision (Vanneste, 1986). For ^{60}Co two rather precise results were reported (*i.e* $A = -1.01(2)$ (Chirovsky *et al.*, 1980) and $A = 0.972(34)$ (Hung *et al.*, 1976)), but as logft = 7.5 for this transition the effect of recoil effects like weak magnetism may be important in this case. The possibilities of Gamow-Teller transitions to search for exotic weak interactions has thus not extensively been explored yet.

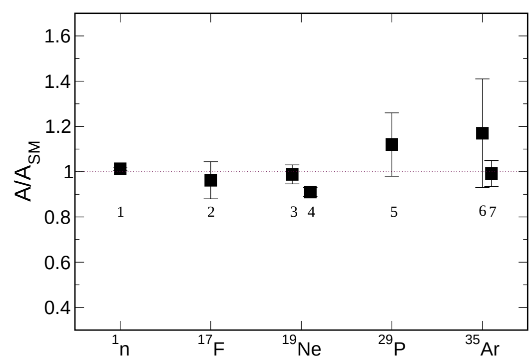

FIG. 24 Results of the β asymmetry parameter measurements for the mixed transitions of the T=1/2 mirror nuclei. For the neutron the weighted average value (Eidelman *et al.*, 2004) is shown. The standard model values were calculated from the experimental ft-values (Naviliat-Cuncic *et al.*, 1991). Note that the second result for ^{19}Ne (Schreiber, 1983) was never published. More details can be found in Table VIII. (1: Eidelman *et al.*, 2004; 2: Severijns *et al.*, 1989; 3: Calaprice *et al.*, 1975; 4: Schreiber, 1983; 5: Masson and Quin, 1990; 6: Garnett *et al.*, 1988; 7: Converse *et al.*, 1993)

Isotope	A/A_{SM}	A	A_{SM}	ft-value (s)
^{1}n	0.9995(95)	$-0.1173(13)^{1}$	$-0.11736(12)$	1052.7(10)
^{17}F	0.962(82)	$0.960(82)^{2}$	0.99715(16)	2314.0(69)
^{19}Ne	0.988(42)	$-0.0391(14)^{3}$	$-0.03957(80)$	1725.1(44)
^{19}Ne	0.910(20)	$-0.0363(8)^{4}$	$-0.03991(16)$	1726.8(4)
^{29}P	1.12(14)	$0.681(86)^{5}$	0.6061(44)	4869(17)
^{35}Ar	1.14(23)	$0.49(10)^{6}$	0.4303(84)	5718(14)
^{35}Ar	0.992(57)	$0.427(23)^{7}$	0.4303(84)	5718(14)

TABLE VIII Results of the β asymmetry parameter measurements for the mixed β transitions of the T=1/2 mirror nuclei. [1]: Eidelman *et al.* (2004); [2]: Severijns *et al.* (1989); [3]: Calaprice *et al.* (1975); [4]: Schreiber (1983); [5]: Masson and Quin (1990); [6]: Garnett *et al.* (1988); [7]: Converse *et al.* (1993). ft-values are from (Naviliat-Cuncic *et al.*, 1991).

At present, several new efforts in this domain are ongoing. At the Los Alamos National Laboratory a MOT-based experiment is being carried out (Crane *et al.*, 2001; Vieira *et al.*, 2000). ^{82}Rb ions from an isotope separator are transformed into atoms, using a Zr catcher foil, and trapped into a first MOT. The trapped atoms are then transferred with a laser push beam to a second MOT where they are re-trapped and polarized by optical pumping. Applying a rotating bias field with which the nuclear spin vector is aligned then permits to measure with a single detector the β asymmetry parameter A as a function of the β particle energy and the angle between the β particle and the nuclear spin vector. A precision at the 1% accuracy level is aimed at (Hausmann *et al.*, 2004).

At Leuven a new set-up to polarize nuclei using the method of low temperature nuclear orientation (Postma and Stone, 1986; Vanneste, 1986) has recently become operational (Kraev *et al.*, 2005). The set-up includes a 17 T superconducting magnet and a Si pin-diode particle detector operating at a temperature of about 10 K. The nuclei are embedded in a non-magnetic host lattice in order to avoid uncertainties related to the lattice position of the nuclei when hyperfine fields in magnetic host lattices are used to polarize nuclei. Here too a precision below 1% is envisaged.

Finally, another type of β asymmetry measurement to search for tensor currents is being prepared (Severijns, 2005; Severijns *et al.*, 2005) at the ISOLDE facility, using the NICOLE low temperature nuclear orientation set-up. It is a relative measurement of the β asymmetry parameter for two isotopes of a single element, one decaying via a β^+ transition the other via a β^- transition. Such relative measurements have a two times higher sensitivity to tensor currents compared to a single absolute measurement and, in addition, are less affected by systematic effects.

4. Limits from other fields

It was recently shown (Campbell and Maybury, 2005) that limits on induced pseudo-scalar interactions, which are strongly constrained by data on $\pi^\pm \to l^\pm \nu_l$ decay, imply limits on the underlying fundamental scalar interactions that are, in certain cases, up to an order of magnitude stronger than limits on scalar interactions from direct β decay searches. However, if the new physics responsible for the effective scalar interactions arises at the electroweak scale from the explicit exchange of new scalars, limits from direct β decay searches are comparable to those from $\pi^\pm \to l^\pm \nu_l$ decay. Depending on the underlying assumptions, the indirect limits from this decay can even be weaker than the β decay limits, leaving the interest in searches for new scalar interactions in β decay experiments undiminished.

Limits on scalar and tensor couplings are also obtained from K_{e3} and $K_{\mu 3}$ decays (Eidelman *et al.*, 2004), and from the purely leptonic decay of the muon (Fetscher and Gerber, 1995, 1998; Herczeg, 1995a; Kuno and Okada, 2001). It is to be noted that K-decay, muon decay and β decay yield complementary information.

Recently, the PIBETA Collaboration has found a strong deficit of the branching ratio of the radiative decay of positive pions at rest in the high-E_γ/low-E_e kinematic region (Frlez *et al.*, 2004). The same anomaly was observed before in another experiment, although with less statistical significance (Bolotov *et al.*, 1990). This deficit could be caused by an inadequacy of the present $V-A$ description of the radiative pion decay, along with the radiative corrections, or by a small admixture of new tensor interactions which may arise due to exchange of new spin one chiral bosons which interact anomalously with matter (Chizhov, 2004; Frlez *et al.*, 2004). This result clearly calls for further theoretical and experimental work.

Finally, Ito and Prézeau (2005) derived order of magnitude constraints $|(C_S - C'_S)/C_V| < 10^{-3}$ and $|(C_T - C'_T)/C_A| < 10^{-2}$ from the upper limit on the neutrino mass. These results are complementary to those from measurements of b, which are sensitive to $(C_S + C'_S)$ and $(C_T + C'_T)$ and measurements of a, which are sensitive to $|C_S|^2 + |C'_S|^2$ and $|C_T|^2 + |C'_T|^2$.

C. Parity violation

Whereas the violation of parity in the weak interaction was discovered almost 50 years ago (Wu *et al.*, 1957), its origin is still today not understood. The most popular models explaining the seemingly maximal violation of parity in the weak interaction are so-called left-right symmetric models (Sec. II.E).

Constraints on right-handed currents from β decay come from longitudinal positron polarization experiments with unpolarized nuclei (Carnoy *et al.*, 1990; van Klinken *et al.*, 1983; Wichers *et al.*, 1987), measurements of the longitudinal polarization of positrons emitted by polarized nuclei (Allet *et al.*, 1996; Camps, 1997; Severijns *et al.*, 1993, 1998; Thomas *et al.*, 2001), experiments in neutron decay (Abele, 2000; Deutsch, 1999; Kuznetsov *et al.*, 1995; Serebrov *et al.*, 1998) and the $\mathcal{F}$t values of the superallowed $0^+ \rightarrow 0^+$ transitions (Hardy and Towner, 2005b).

There is strong interest in more precise tests of maximal parity violation in nuclear β decay as these would provide new constraints on models with exotic fermions, with leptoquark exchange or with contact interactions (Herczeg, 2001).

1. $\mathcal{F}$t value of superallowed Fermi transitions

The average $\mathcal{F}$t value for the superallowed $0^+ \rightarrow 0^+$ pure Fermi transitions provides a stringent constraint on the mixing angle ζ between the left- and right-handed W gauge bosons. In a model where right-handed currents are assumed, one can write the $\mathcal{F}$t value as

$$\mathcal{F}t = \frac{K}{2G_F^2 V_{ud}^2 (1-2\zeta)(1+\Delta_R^V)} \tag{110}$$

Using the previously cited value $\mathcal{F}$t = 3073.5(12) s (Hardy and Towner, 2005b) and the values for $|V_{us}|$ and $|V_{ub}|$ recommended by the Particle Data Group (Eidelman *et al.*, 2004), and requiring that V_{ud}^2 satisfies unitarity, Hardy and Towner (2005b) found $\zeta = 0.0018(7)$. This value deviates by about 2.5σ from zero, the value that corresponds to maximal parity violation. However, when the above mentioned weighted average of the new values for V_{us} obtained from measurements in K decays is used (*viz.* $|V_{us}| = 0.2251(21)$; Sec. IV.A.4), one has $\zeta = 0.0006(7)$. The mixing angle for the left- and right-handed gauge bosons is thus clearly limited to the milliradian region: $-0.0006 \leq \zeta \leq 0.0018$ (90 % C.L.). This is currently the strongest limit on ζ from β decay.

2. Beta-asymmetry parameter

Parity violation in the weak interaction was first observed by measuring the asymmetry parameter A in the $(5^+ \rightarrow 4^+)$ β^- decay of polarized ^{60}Co nuclei (Wu *et al.*, 1957). Twenty years later this experiment was repeated with a more advanced set-up where the nuclear polarization could be rotated using two crossed magnetic coils, yielding $A = -1.01(2)$ (Chirovsky *et al.*, 1984, 1980). Using Eq. (C21) the above result yields a lower limit of 245 GeV/c^2 (90% C.L.) for the mass of a vector boson coupling to right-handed particles (assuming $\zeta = 0$). However, this result should be taken with some caution as long as the effect of recoil order corrections, like weak magnetism, has not been evaluated for this transition.

The problem with recoil corrections can be avoided by measuring the β asymmetry parameter A in the β decay between analog states of $T = 1/2$ mirror nuclei. Due to the superallowed character of these mirror β transitions nuclear structure dependent corrections are very small. A survey of the sensitivity of such experiments for the mixed transitions of $T = 1/2$ mirror nuclei from ^{11}C up to ^{43}Ti has indicated (Naviliat-Cuncic *et al.*, 1991) that for most transitions the required experimental precision is of the order of 0.5% in order to be sensitive to a right-handed boson mass of 300 GeV/c^2 (90% C.L.). This requires a very precise determination of the degree of nuclear polarization. A way to overcome this difficulty of absolute measurements is to carry out relative measurements, comparing the asymmetry parameter for the mixed mirror β transition to that of a pure Gamow-Teller transition from the same isotope. This is possible for several mirror nuclei, such as ^{21}Na, ^{23}Mg, ^{29}P and ^{35}Ar, and was demonstrated in the case of ^{29}P (Masson and Quin, 1990) and ^{35}Ar (Converse *et al.*, 1993). Since all β transitions have the same sensitivity to δ^2 ($\delta = (m_1/m_2)^2$, with m_1 (m_2) the mass of the W_1 (W_2) boson; see Sec.II.E) independent of their Fermi/Gamow-Teller character (see Eq. (C22)), the sensitivity to δ^2 is lost in such relative measurements.

In order to obtain a competitive limit for the mass of a W_R boson, a precision of at least 0.5% is needed, both for pure Gamow-Teller transitions and for the $T = 1/2$ mirror β transitions.

3. Longitudinal polarization

The early measurements of the longitudinal polarization, P_L, of beta particles from unpolarized nuclei in pure Fermi and pure Gamow-Teller transitions have reached a precision of a few percent (van Klinken *et al.*, 1983, 1978). However, the uncertainties in the recoil order corrections in the decays of ^{32}P and ^{60}Co used in those measurements, hamper the extraction of reliable conclusions on weak interaction properties. The only measurement free of this problem is that for the mixed transition in the decay of tritium which yielded $P_L = -1.005(26)$ (Koks and Van Klinken, 1976). However, it has been pointed out previously (Deutsch and Quin, 1995) that some additional concern regarding the accuracy of Mott scattering polarimetry for very low electron energies (Fletcher *et al.*, 1986) may make the error estimate of this measurement optimistic.

Sub-percent sensitivity was reached only in relative measurements (Carnoy *et al.*, 1990, 1991; Skalsey *et al.*, 1989; Wichers *et al.*, 1987) where the ratio of the longitudinal polarization in pure Fermi and pure Gamow-Teller transitions was determined. This ratio is sensitive to the product $\delta\zeta$

$$P_L^F / P_L^{GT} \simeq 1 + 8\delta\zeta \; . \tag{111}$$

All measurements performed so far have been carried out in β^+ transitions. In the first experiment

(Wichers *et al.*, 1987) the positron polarization was determined using Bhabha scattering. Later experiments (Carnoy *et al.*, 1990, 1991; Skalsey *et al.*, 1989) used the method of time-resolved spectroscopy of positronium hyperfine states. This technique makes use of the magnetic field dependence of both the lifetime and the population of the singlet and the $m = 0$ triplet positronium states (Carnoy *et al.*, 1991; Dick *et al.*, 1963; Van House and Zitzewitz, 1984). The weighted average result of all these experiments yielded $-4.0 < \delta\zeta \times 10^4 < 7.0$ (90% C.L.) (Carnoy *et al.*, 1990). Note that, although these limits are very stringent, they are not sensitive to the mass of a possible W_2-boson with right-handed couplings in the limit $\zeta = 0$ (Sec. IV.C.1 and Fig. 26).

4. Polarization asymmetry correlation

Limits on right-handed currents complementary to those presented above and also more stringent, can be obtained from the measurement of the longitudinal polarization of β particles emitted by polarized nuclei, the so-called polarization-asymmetry correlation (Quin and Girard, 1989). This observable determines the parameter $(\delta + \zeta)^2$ which is sensitive to δ and hence to the mass of a right-handed W_2 boson even when $\zeta = 0$. Four measurements of this correlation were carried out, all using the method of time-resolved spectroscopy of positronium hyperfine states to determine the longitudinal polarization of the decay positrons. The experimental quantity that was addressed was either the ratio of positron polarizations P^- and P^+ for positrons emitted in two opposite directions with respect to the nuclear spin direction, or the ratio of the polarization of positrons emitted opposite to the nuclear spin direction, P^-, and emitted by unpolarized nuclei, P^0. In the first case

$$P^-/P^+ = R_0 \left[1 - \frac{8\beta^2 \boldsymbol{\beta}\cdot\mathbf{J}A}{\beta^4 - (\boldsymbol{\beta}\cdot\mathbf{J}A)^2}(\delta+\zeta)^2\right], \qquad (112)$$

where

$$R_0 = \left[\frac{\beta^2 - \boldsymbol{\beta}\cdot\mathbf{J}A}{\beta^2 + \boldsymbol{\beta}\cdot\mathbf{J}A}\right]\left[\frac{1 + \boldsymbol{\beta}\cdot\mathbf{J}A}{1 - \boldsymbol{\beta}\cdot\mathbf{J}A}\right], \qquad (113)$$

is the standard model expectation value for P^-/P^+, $\beta = v/c$ and $\boldsymbol{\beta}.\mathbf{J}A$ the experimental β asymmetry. In the second case

$$P^-/P^0 = R_0 \left[1 - \frac{4\boldsymbol{\beta}\cdot\mathbf{J}A}{\beta^2 - (\boldsymbol{\beta}\cdot\mathbf{J}A)}(\delta+\zeta)^2\right], \qquad (114)$$

with

$$R_0 = \frac{\beta^2 - \boldsymbol{\beta}\cdot\mathbf{J}A}{\beta^2(1 - \boldsymbol{\beta}\cdot\mathbf{J}A)}\,. \qquad (115)$$

As can be seen, interesting candidates for this type of experiments are nuclei for which a large degree of nuclear polarization can be obtained and which decay via a pure Gamow-Teller transition of the type $J \to J-1$, *i.e.* with a maximal asymmetry parameter $A = 1$. The sensitivity of the $T = 1/2$ mirror β transitions has also been considered (Govaerts *et al.*, 1995). Due to the relative character of this type of measurements a number of systematic effects are reduced significantly or even eliminated.

The first measurement of this type (Severijns *et al.*, 1993), at the LISOL isotope separator coupled to the CYCLONE cyclotron in Louvain-la-Neuve, used the isotope ^{107}In ($t_{1/2}$ = 32.4 m) (Fig. 25), which was polarized with the method of low temperature nuclear orientation (Postma and Stone, 1986; Vandeplassche *et al.*, 1981). This technique combines temperatures in the millikelvin region obtained in a ^{3}He-^{4}He dilution refrigerator, with the large magnetic hyperfine fields, ranging from a few Tesla to several hundreds of Tesla, that impurity nuclei feel in a ferromagnetic host lattice. The second measurement, carried out at the Paul Scherrer Institute, used ^{12}N that was produced and polarized in the $^{12}C(\vec{p}, n_0)^{12}\vec{N}$ polarization transfer reaction initiated by a 70% polarized proton beam (Allet *et al.*, 1996). With each isotope two measurements were performed, the second one always after considerable improvements of the experimental set-up. For ^{107}In an experimental β asymmetry $\boldsymbol{\beta}\cdot\mathbf{J}A \simeq 0.50$ was obtained, corresponding to a nuclear polarization of $\sim$ 65%. The final result was $(\delta + \zeta)^2 = 0.0021(17)$ (Camps, 1997; Severijns *et al.*, 1998). With ^{12}N an experimental β asymmetry $\boldsymbol{\beta}\cdot\mathbf{J}A \simeq 0.13$ was obtained, corresponding to a nuclear polarization of $\sim$ 15%. This experiment yielded $(\delta + \zeta)^2 = -0.0004(32)$ (Thomas *et al.*, 2001). If interpreted in manifest left-right symmetric models, these results correspond to a lower limit for the mass of a W_2 vector boson with right-handed couplings of 303 GeV/c^2 and 310 GeV/c^2 (90% C.L.). These are the most sensitive tests of parity violation in nuclear beta decay to date. The lower limit from the combined result of both experiments is 320 GeV/c^2 (90% C.L.).

A similar experiment was carried out with the mirror nucleus ^{21}Na, produced with a deuteron beam from the University of Wisconsin tandem electrostatic accelerator. The ^{21}Na was polarized with circularly polarized light from a copper-vapor-laser-dye-laser system tuned to the sodium D_1 line. The result $(\delta + \zeta)^2 = -0.037(70)$ (Schewe *et al.*, 1997) is in agreement with the measurements on ^{107}In and ^{12}N.

Finally, a measurement of the polarization asymmetry correlation was also carried out with ^{118}Sb at the ISOLDE-CERN isotope separator facility. This experiment (Vereecke, 2001) has explored the limits of sensitivity of this type of experiments when the technique of low temperature nuclear orientation is used to polarize the nuclei. The analysis of the data showed that this method is limited by the present knowledge of the spin rotation of positrons when being scattered in the iron host foil in which the nuclei have to be implanted in order to be polarized. As the nuclear polarization obtained in polar-

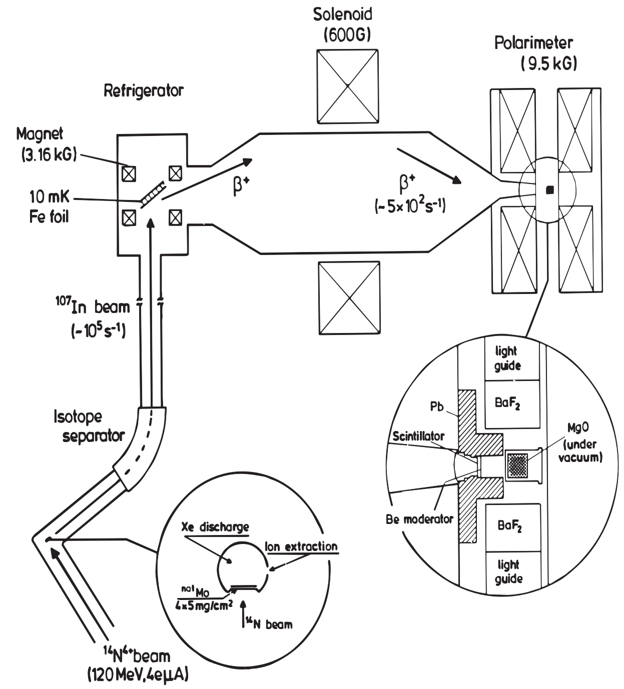

FIG. 25 Experimental set-up to measure the longitudinal polarization of positrons emitted in the decay of polarized ^{107}In nuclei. The radioactive ions delivered by the isotope separator are implanted and oriented in an iron foil at a temperature of 10 mK inside a dilution refrigerator. The positrons emitted in the decay of the polarized nuclei are energy-selected with a spectrometer and then slowed down and stopped in a MgO pellet. One plastic and two BaF_2 scintillator detectors observe the decay of the positronium that is formed in the MgO, from which the longitudinal polarization of the positrons is then obtained. From Severijns *et al.* (1993).

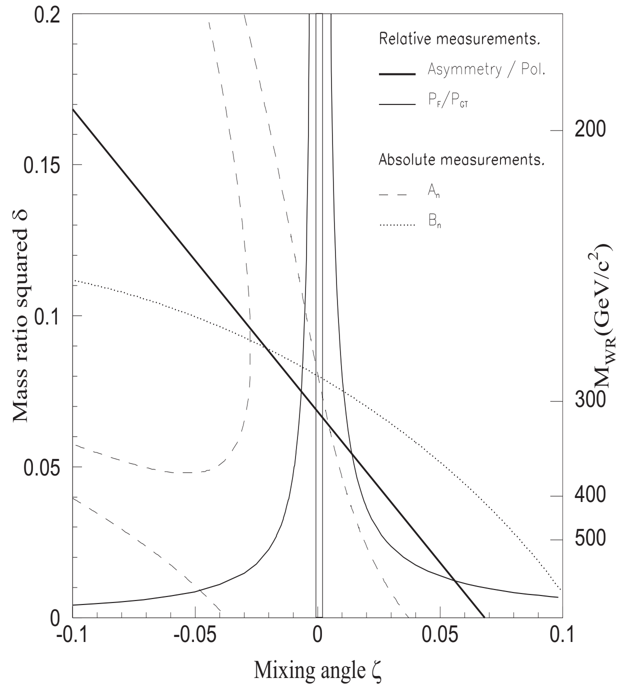

FIG. 26 Constraints (90% C.L.) on the right-handed current parameters δ and ζ from the nuclear β decay experiments discussed here. The allowed regions are those containing $(\delta, \zeta) = (0, 0)$. The narrow vertical band around $\zeta = 0$ is the region allowed by unitarity and the $\mathcal{F}t$ value for the superallowed Fermi transitions (Sec. IV.C.1). Adapted from Thomas *et al.* (2001).

ization transfer reactions is rather small (Miller *et al.*, 1991), significant progress can not be expected from this method either. An interesting option in this respect, circumventing the above mentioned difficulties, would be to couple a β polarimeter to an ion or atom trap containing a nuclear polarized sample.

5. Neutron decay

The correlation coefficients in neutron decay that are most sensitive to parity violation are the β asymmetry parameter A and the neutrino asymmetry parameter B.

In Fig. 26 the limits for the right-handed current parameters δ and ζ (in manifest left-right symmetric models) from the A and B parameters in neutron decay (Eidelman *et al.*, 2004) are compared to the limits from superallowed β-decay, the P_F/P_{GT} measurements and the polarization-asymmetry correlation measurements discussed in the previous paragraphs (see also Abele (2000)).

The available values for the neutrino asymmetry parameter B are very consistent with each other (see Table IV). The precision was significantly increased in the two most recent measurements, which were both performed with cold polarized neutrons at the WWR-M reactor of the Petersburg Nuclear Physics Institute (PNPI) (Kuznetsov *et al.*, 1995; Serebrov *et al.*, 1998). The set-up that was used is shown schematically in Fig. 27. The momentum and angle of escape of the undetected antineutrino were deduced from the coincident detection of the decay electron and recoil proton, and the subsequent measurement of their momenta. The electrons were detected with a plastic scintillator. The protons were accelerated and focused by an electric field onto the proton detector which consisted of an assembly of two microchannel plates. This permitted to determine the time of flight of each proton with an accuracy of 10 ns. The weighted averaged result of the two measurements, $B = 0.9821(40)$ yields a lower limit of 280 GeV/c^2 (90 % C.L.) for the mass of a W_2 boson with right-handed couplings (Fig. 26).

Recently a measurement of the neutrino asymmetry parameter B was also performed with the PERKEO II set-up (Fig. 16) at the ILL (Kreuz, 2003). The electron and the proton from the neutron decay were guided by a 1 T magnetic field towards two combined electron and proton detectors. In order to better control systematics a detection system which is able to detect both particles in

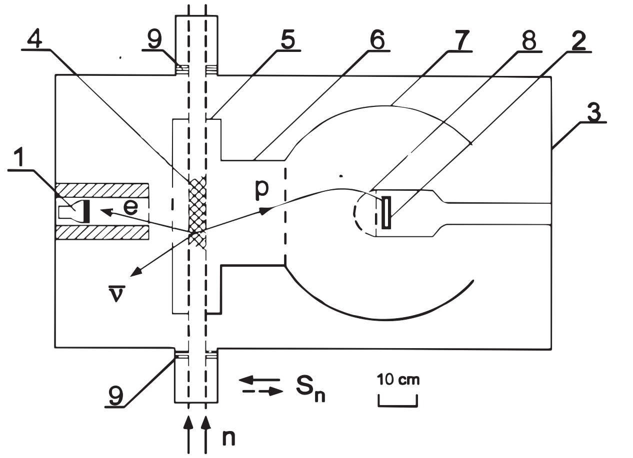

FIG. 27 Experimental apparatus for measuring the B-parameter in neutron decay. (1) Electron detector, (2) proton detector, (3) vacuum chamber, (4) decay region, (5) cylindrical electrode, (6) TOF chamber, (7) spherical electrode, (8) spherical grid, and (9) LiF diaphragm. From Kuznetsov *et al.* (1995).

both detectors was chosen. The electrons are detected by plastic scintillators in combination with photomultipliers. The protons are accelerated by a negative potential towards a thin carbon foil where they create secondary electrons which can then be detected in the electron detector. Since the electric potential is considerably lower than the electron energies observable in the experiment (threshold 60 keV), the electrons pass the foils unhindered. This method reduces systematics and increases the sensitivity. The analysis is still ongoing.

6. Comparison with other fields

A recent new determination of the Michel parameter ρ in muon decay by the TWIST Collaboration at TRIUMF (Musser *et al.*, 2005) has yielded an upper limit $|\zeta| <0.030$ (90% C.L.) on the $W_L - W_R$ mixing angle. A measurement of the muon decay parameter δ by the same collaboration (Gaponenko *et al.*, 2005) yielded a lower limit on the W_R mass of 420 GeV/c^2 (90 % C.L.). Both experiments improved slightly on the earlier results reported by Jodidio *et al.* (1986, 1988). The longitudinal polarization of positrons emitted from polarized muons has been remeasured at PSI Morelle (2002). The result is expected to provide a new value of the Michel parameter ξ" with significantly higher precision but the anticipated limit on W_R is, however, not expected to be improved.

In manifest left-right symmetric models the limits from β decay (Fig. 26) and from muon decay for the mass of a W_R boson with right-handed couplings are weaker than the lower limit of 715 GeV/c^2 from a simultaneous fit to the charged and neutral sectors (Czakon *et al.*, 1999) and the lower limit of 786 GeV/c^2 for the mass of a heavy W' boson from $p\overline{p}$ collisions at Fermilab (Affolder *et al.*, 2001). However, results from β decay, from muon decay and from collider experiments are complementary when interpreted in more general left-right symmetric extensions of the standard model, such as models with different gauge coupling constants or different CKM matrices in the left- and right-handed sectors, etc. This is illustrated in Fig. 28. The complementarity between experiments at low and at high energies is also discussed by Langacker and Uma Sankar (1989) and Herczeg (2001). Note also that experiments in β decay and in muon decay are sensitive to the helicity of a heavy W gauge boson, while $p\overline{p}$ collisions are not.

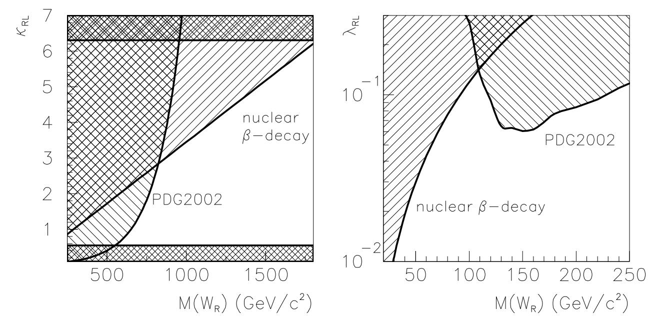

FIG. 28 Exclusion plots on parameters of generalized left-right symmetric extensions of the standard model. The parameter $\kappa_{RL} = g_R/g_L$ characterizes the intrinsic gauge coupling of the right-handed sector relative to the left-handed one, while $\lambda_{RL} = |V^R_{ud}|/|V^L_{ud}|$ denotes the relative coupling strength of first generation quarks to an hypothetical right-handed gauge boson with mass $M(W_R)$. The hatched areas are excluded either by direct searches at colliders (PDG2002) or by precision experiments in nuclear β decay. The horizontal bands in the left panel are bounds from theory. The contours in the left panel assume $|V^R_{ud}| = |V^L_{ud}|$; those in the right panel assume $g_R = g_L$. Adapted from Thomas *et al.* (2001).

Generally the weak interaction is ignored in atomic physics, because it is much weaker than the electromagnetic interaction. However, the valence electrons of an atom can experience the weak interaction. Indeed, the neutral vector boson, Z^0, can be exchanged between a nucleon and a valence electron, provided the electron wave function has a non-zero amplitude at the nucleus since the exchange is effectively a point-like interaction. This means that parity-violation can be observed in atomic transitions. Precise measurements of this atomic parity non-conservation provide an important low-energy test of the electroweak standard model, complementary to nuclear physics and particle physics experiments. Reviews were published by Bouchiat and Bouchiat (1997) and Haxton and Wieman (2001).

D. Time reversal violation

At present there are two unambiguous pieces of evidence for time reversal violation (T-violation) and CP-violation, i.e. the decay of neutral K- and B-mesons (Alavi-Harati *et al.*, 2000; Browder and Facini, 2003; Christenson *et al.*, 1964; Fanti *et al.*, 1999), and the excess of baryonic matter over antimatter in the Universe (Riotto and Trodden, 1999). However, the CP-violation that is observed in K- and B-meson decays, and which can be incorporated in the standard model via the quark mixing mechanism, is too weak to explain the excess of baryons over antibaryons. Cosmology therefore provides a hint for the existence of an unknown source of T-violation that is not included in the standard model.

The standard model predictions of T-violation, originating from the quark mixing scheme, for systems built up of u and d quarks are by 7 to 10 orders of magnitude lower than the experimental accuracies presently available (Herczeg and Khriplovich, 1997). Thus, because standard model contributions to T-violating electric dipole moments and T-violating correlations in decay or scattering processes are so strongly suppressed, any sign for the presence of T-violation in these observables or processes would be a signature of a new source of T-violation. New T-violating phenomena may be generated by several mechanisms (Herczeg, 2001) like the exchange of multiplets of Higgs bosons, leptoquarks, right-handed bosons, etc. These exotic particles may generate scalar or tensor variants of the weak interaction or a phase different from 0 or π between the vector and axial-vector coupling constants. It is a general assumption that T-violation may originate from a tiny admixture of such new exotic interaction terms. Weak decays provide a favorable testing ground in a search for such new feeble forces (Boehm, 1995; Herczeg, 1995b).

Direct searches for time reversal violation via correlation experiments in β decay require the measurement of terms including an odd number of spin and/or momentum vectors. The D triple correlation $\mathbf{J} \cdot (\mathbf{p_e} \times \mathbf{p_\nu})$ is sensitive to P-even, T-odd interactions with vector and axial-vector currents. To determine this correlation, the momenta of the β particle and neutrino emitted in mutually perpendicular directions in a plane perpendicular to the nuclear spin axis is to be determined. It also requires the use of mixed transitions (see Eq. (B7)). As an example, for the neutron the standard model prediction for the magnitude of this correlation coefficient, based on the observed CP-violation, is $D < 10^{-12}$ (Herczeg and Khriplovich, 1997). Any value above the final state effect level, which is typically $D_{FSI} \approx 10^{-5}$, would thus indicate new physics. For leptoquark models this experimental range is not excluded by measurements of other observables, like electric dipole moments (Herczeg, 2001) (see also Sec. IV.D.3).

The other important correlation with respect to searches for T-violation in β decay is the R triple correlation $\boldsymbol{\sigma} \cdot (\mathbf{J} \times \mathbf{p_e})$, Eq. (B10), which probes P-violating components of T-violating scalar and tensor interactions. To determine the R-correlation the transverse polarization of β particles emitted in a plane perpendicular to the polarized nuclear spin axis is to be determined.

Measurements of the D- and R-triple correlations are very difficult as they require the use of polarized nuclei and at the same time the determination of either the neutrino momentum through the recoil ion (D-correlation), or of the transverse polarization of the β particle (R-correlation).

1. D-correlation

The D-correlation was measured in neutron decay and for ^{19}Ne. Early measurements in neutron decay have yielded $D_n = -0.0011(17)$ (Steinberg *et al.*, 1974), $D_n = -0.0027(50)$ (Erozolimskii *et al.*, 1974) and $D_n = 0.0022(30)$ (Erozolimskii *et al.*, 1978). Two new and more precise measurements of D_n have recently been carried out, one at NIST (Lising *et al.*, 2000) and the other at the ILL (Soldner *et al.*, 2004).

In the *emiT* experiment at NIST a beam of cold neutrons is polarized and collimated before it passes through a detection chamber with four electron and four proton detectors in an octagonal arrangement (Fig. 29). The octagonal geometry places electron and proton detectors at relative angles of 45° and 135°. Coincidences are counted between detectors at relative angles of 135°. While the cross product $\mathbf{p_e} \times \mathbf{p}_\nu$ is largest at 90°, the preference for larger electron-proton angles in the decay makes placement of the detectors at 135° the best choice to achieve greater symmetry, greater acceptance and greater sensitivity to D (Lising *et al.*, 2000), compared to previous experiments which detected coincidences at 90°. Another important improvement is the larger polarization, which is 96(2)% compared to about 70% previously. The initial run with this new set-up produced a statistically limited result of $D_n = [-0.6 \pm 1.2(stat) \pm 0.5(syst)] \times 10^{-3}$ (Lising *et al.*, 2000). A second run, with an improved set-up (Mumm *et al.*, 2004) and aiming at a sensitivity of about 2 $\times 10^{-4}$ or better, was in the mean time completed.

The TRINE experiment at the ILL, detects the neutron decay electrons by four plastic scintillators in coincidence with multiwire proportional chambers. Four PIN diodes with thin entrance windows are used for detecting the protons. These are accelerated onto the PIN diodes in a focusing electrostatic field provided by a high voltage electrode. The neutron beam polarization was 97.4(26)%. The main advantage of TRINE with respect to other experiments is the suppression of systematic effects that is obtained by using the spatial resolution of the wire chambers and the high segmentation with 12 detector planes. In addition, thanks to the large signal to background ratio, the statistics of the neutron beam can be used completely. This resulted in $D_n = [-2.8 \pm 6.4(stat) \pm 3.0(syst)] \times 10^{-4}$ (Soldner *et al.*,

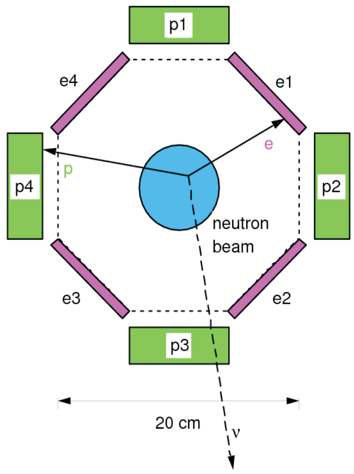

FIG. 29 Principle of the *emi*T experiment to test time reversal violation using an octagonal array of four each proton (P) and electron (E) detectors. Adapted from Lising *et al.* (2000).

2004). A new measurement with TRINE with improved statistics and systematics was in the mean time carried out (Plonka, 2004). Together with the new data from *emi*T the world average for D in neutron decay will soon reach a precision in the very interesting range of 10^{-4}.

The most precise measurements of the D-correlation in the decay of the mirror nucleus ^{19}Ne have yielded $D = -0.0005(10)$ (Baltrusaitis and Calaprice, 1977) and $D = 0.0004(8)$ (Hallin *et al.*, 1984). These experiments have reached the limit imposed by final state effects, which is at the 10^{-4} level (Calaprice, 1985). The combined result, $D = 0.0001(6)$ (Calaprice, 1985) is at present the most precise limit on a T-violating angular correlation in a weak decay process. These measurements were also the first ever to test T-invariance in any weak process at a level below the characteristic K-decay CP violation of 2.3 $\times 10^{-3}$ (Christenson *et al.*, 1964) without any evidence for a violation of T-invariance.

No sign for T-violation in the V-A weak interaction was thus observed in nuclear beta decay so far.

2. R-correlation

Only two R-correlation measurements were carried out in nuclear β decay. The first with ^{19}Ne (Schneider *et al.*, 1983) and the second with ^{8}Li (Huber *et al.*, 2003; Sromicki *et al.*, 1996).

The ^{19}Ne (Schneider *et al.*, 1983) was polarized to essentially 100% by deflection of an atomic beam in a "Stern-Gerlach" magnet. The polarized beam was captured in a holding cell which assured a spin holding time that was long compared to the decay lifetime. The transverse spin component of the β particles emitted perpendicularly to the nuclear spin polarization was analyzed with four identical large acceptance Mott scattering polarimeters with detector telescopes. A non-zero value of the R-triple correlation coefficient would lead to a left-right asymmetry in the scattering of the β particles by a gold Mott analyzing foil. The polarimeter analyzing power was a few percent. The final result of this measurement was $R(^{19}\mathrm{Ne}) = 0.079(53)$, the error being limited only by statistics.

A high-precision measurement of the R-parameter was carried out in the 1990's for the Gamow-Teller decay of ^{8}Li at the Paul Scherrer Institute (Huber *et al.*, 2003; Sromicki *et al.*, 1996). The set-up for this experiment (Fig. 30) has continuously been improved and upgraded to finally reach a precision of 2×10^{-3}. Polarized ^{8}Li nuclei were produced by a vector-polarized deuteron beam on an enriched ^{7}Li metal target. This was cooled to liquid helium temperature in order to achieve a long polarization relaxation time ($t \geq 20$s), an order of magnitude longer than the mean lifetime for ^{8}Li ($\tau = 1.21$ s). The transverse polarization of the ^{8}Li decay electrons was deduced from the measured asymmetry in Mott scattering at backward angles using a lead foil as analyzer. To obtain a large solid angle the detectors were arranged in a cylindrical geometry around the ^{8}Li polarization axis. In fact, the set-up was made of four separate azimuthal segments, each containing an upper and a lower telescope, thus providing four independent measurements of the electron polarization. Each telescope consisted of two thin transmission scintillators followed by a thick stopping scintillator. Much attention was paid to the passive shielding of the detectors against background radiation produced in the target area. The weighted average result of six runs is $R(^{8}\mathrm{Li}) = 0.0009(22)$ (Huber *et al.*, 2003). This has been corrected for the effects of the final state interaction which can mimic the genuine time reversal violation in the R-correlation and which was calculated to be $R_{FSI} = 0.7(1) \times 10^{-3}$. This has improved by about an order of magnitude the bounds for T-violating tensor couplings, yielding $-0.008 < Im(C_T + C'_T)/C_A < 0.014$ (90% C.L.).

The above mentioned result from ^{19}Ne (Schneider *et al.*, 1983) is in principle sensitive to both T-violating scalar as well as tensor couplings but rather weak limits were obtained due to the limited experimental precision. A high precision test for the presence of a T-violating scalar component thus still remains to be done. Therefore, the R-correlation in neutron decay is now investigated at the polarized cold neutron facility FUNSPIN (Bodek *et al.*, 2000; Zejma *et al.*, 2005) at the spallation source SINQ at the Paul Scherrer Institute. This experiment (Bodek *et al.*, 2003) aims at a 0.5% measurement by determining the transverse polarization of electrons emitted in polarized neutron decay using large angle Mott scattering. Electrons emitted from polarized neutrons and scattered from a Pb analyzer foil are tracked by a system of two multiwire gas chambers and stopped in a plastic scintillator (Fig. 31). True events, where the electron emitted

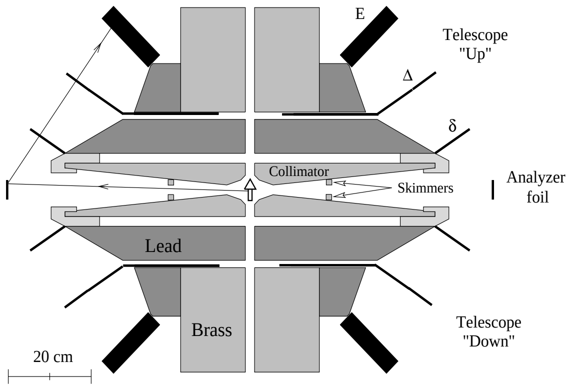

FIG. 30 Vertical cross section through the Mott polarimeter used in the ^{8}Li R-correlation experiment. The direction of incidence of the polarized deuteron beam is perpendicular to the figure. The central arrow indicates the direction of the ^{8}Li spin in the target. A trajectory of an electron scattered on the lead analyzer foil is also shown. The labels δ, Δ and E refer to two delta-E detectors and the energy detector. More details are given in the text. From Huber *et al.* (2003).

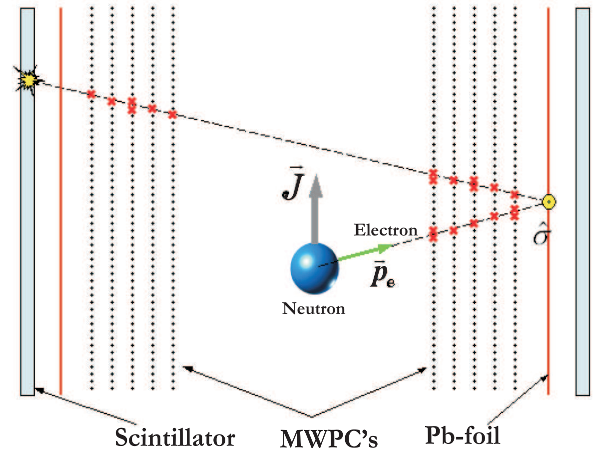

FIG. 31 Principle of the R-correlation experiment in neutron decay determining the amplitude of $\boldsymbol{\sigma} \cdot (\mathbf{J} \times \mathbf{p_e})$. The labels E and V refer to the energy detector and the veto detector. More details are given in the text. Adapted from Bodek *et al.* (2003).

in the neutron decay was scattered from the analyzing foil, can thus be selected by the reconstruction of the scattering vertex and the electron energy information, thereby significantly reducing the background. From the electron tracks, the scattering angle and the Mott scattering asymmetry can be determined. The apparatus permits a simultaneous determination of the time reversal invariant N correlation parameter, Eq. (B9) at the 5% (relative) level. Because N is proportional to A (*viz.* $N_{SM} = -(\gamma m_e/E_e)A_{SM} \simeq 0.119 m_e/E_e$) and A has been measured to the 1% level, determining N provides a calibration of the apparatus. Final state effects contribute only at the level of 0.001, which is beyond the expected accuracy on the R-coefficient.

Finally, it is to be noted that several other correlations in neutron and nuclear β decay are also sensitive to T-violating couplings, either through final-state interaction effects such as the β asymmetry parameter A and the longitudinal beta particle polarization G, or through a quadratic dependence on the norm of the coupling constants, as is the case for the β-ν correlation coefficient a. In this way, experimental limits on T-violating couplings, although being somewhat less stringent, were obtained from the longitudinal positron polarization in the decay of several light nuclei (Carnoy *et al.*, 1991), from the positron-neutrino correlation in the $0^+ \rightarrow 0^+$ decay of ^{32}Ar (Adelberger *et al.*, 1999) and from the polarization asymmetry correlation for positrons in the decay of polarized ^{107}In (Severijns *et al.*, 1998).

3. Comparison with other fields

T-violating and P-conserving "D-type" correlations as well as T-violating and P-violating "R-type" correlations were also investigated in the decay of the muon and in decays of kaons and hyperons. In both cases the neutron and nuclear β decays discussed above yielded the most precise results. Other decays are usually about a factor of 5 to 10 or even less precise. For the D-type correlation a precision of a few times 10^{-3} was recently obtained in K^+-decay (Abe *et al.*, 2004). R-type triple correlation experiments in the decays of polarized Λ_0 particles have yielded results that are often one to two orders of magnitude less precise than the R-correlation experiment with ^{8}Li (Sromicki *et al.*, 1996). Recently, a precision of about 8×10^{-3} was obtained for the R-type transverse positron polarization in muon decay (Danneberg *et al.*, 2005).

Another low energy search for time reversal violation is provided by measurements of permanent electric dipole moments (EDM). Since EDM's violate both parity and time reversal, the simultaneous presence of even small amounts of violation of these two discrete symmetries by the fundamental forces would result in small but finite particle EDM's. Experiments searching for particle EDM's have started in the 1950's. They played a crucial role in eliminating theories put forward to explain the observation of CP-violation in the K^0 system, because they usually predicted too large dipole moments. The standard model, however, predicts electric dipole moments that are well below the present experimental sensitivity. EDM experiments are therefore an ideal probe to search for new physics beyond the standard model. Over the years, the accuracy of EDM experiments has improved by 7 to 8 orders of magnitude such that the sizes of EDM's predicted by *e.g.* supersymmetric, left-right symmetric or multi-Higgs models now lie within the detectable range (Pendlebury and Hinds, 2000).

Of the best existing EDM measurements, the current limit on the neutron EDM is 6.3 $\times 10^{-26}$ e·cm (90% C.L.) (Harris *et al.*, 1999), that on the electron is 1.6 $\times 10^{-27}$ e·cm (90% C.L.) (Regan *et al.*, 2002) and that on the Hg atom is 2.1$\times$ 10^{-28} e·cm (95% C.L.) (Romalis *et al.*, 2001). New experiments in neutron decay, aiming at a sensitivity limit of $10^{-28}e$ cm, are being prepared and/or planned at several facilities (*e.g.* (Atchison *et al.*, 2005)). For the electron EDM a significant increase in precision is expected from the use of heavy atoms (Ra) or heavy polar molecules (YbF) which have large enhancement factors, enabling in principle to reach a sensitivity in the $10^{-30}e$ cm range in the next decade. Further, new EDM measurements for the muon and the deuteron are planned too (Aoki *et al.*, 2004; Silenko *et al.*, 2003).

It is to be noted that even though the search for a neutron electric dipole moment restricts the parameter space for many extensions to the standard model (Ellis, 1989), the D-triple correlation is more sensitive to CP violation induced by leptoquarks which appear naturally in Grand Unified Theories (Herczeg, 2001). Although determinations of the R-parameter provide less stringent bounds than what is obtained from experiments searching for atomic and molecular electric dipole moments, the theoretical uncertainties associated with the last ones could be large (Herczeg, 2001) and therefore direct limits on imaginary scalar and tensor couplings from R-correlation measurements would still be useful.

E. Neutrino mass

1. Neutrino oscillations

Another sector of the standard model that is tested in β decay is the one of neutrino masses (McKeown and Vogel, 2004). Whereas the standard model assumes neutrinos to be massless, clear evidence for non-zero neutrino masses were recently found in several types of oscillation experiments. The origin of this was the long standing solar neutrino problem, the large deficit that was observed for the number of detected neutrinos coming from the sun with respect to the amount that was expected on the basis of the Standard Solar Model (Abdurashitov *et al.* (1999); Cleveland *et al.* (1998); Fukuda *et al.* (1994, 1998a); Hampel *et al.* (1999)).

Neutrino oscillations imply that a neutrino from one specific flavor, say a muon neutrino ν_μ, transforms into another flavor eigenstate, *i.e.* an electron neutrino ν_e or a tau neutrino ν_τ, while traveling from the source to the detector. The existence of neutrino oscillations requires *(i)* a non-trivial mixing between the three weak interaction eigenstates (ν_e, ν_μ, ν_τ) and the corresponding neutrino mass states (ν_1, ν_2, ν_3) and *(ii)* that these masses are not degenerate, *viz.* that the mass eigenvalues (m_1, m_2, m_3) differ from each other. Consequently, the experimental evidence of neutrino oscillations proves that at least some neutrinos have non-zero masses. In addition, the existence of neutrino oscillations implies the breakdown of lepton family number conservation.

Evidence for neutrino oscillations was first obtained in measurements observing atmospheric neutrinos which are produced as decay products in hadronic showers caused by collisions of cosmic rays with nuclei in the upper atmosphere. A strong deficit of muon neutrinos was reported by several experiments (Allison *et al.*, 1997; Becker-Szendy *et al.*, 1992; Fukuda *et al.*, 1994, 1998a). Clear evidence for this deficit being caused by neutrino oscillations was obtained from the zenith angle dependence of the flux ratio (Fukuda *et al.*, 1994, 1998b) which showed a clear deficit for the upward-going muon neutrinos, which have to travel through the earth before reaching the detector, in contrast to the downward-going muon neutrinos. The atmospheric neutrino data is consistent with neutrino oscillation from muon neutrinos to tau neutrinos (Fukuda *et al.*, 1998b).

Clear evidence has also been obtained for oscillations of solar neutrinos (Ahmad *et al.*, 2001, 2002a,b) and reactor neutrinos (Ahn *et al.*, 2003; Eguchi *et al.*, 2003), while a number of new experiments to study the nature of neutrino oscillations are in progress or planned as well (McKeown and Vogel, 2004).

2. Absolute neutrino mass determinations

Neutrino oscillation experiments, whether they are observing solar, atmospheric or reactor neutrinos, are only sensitive to the differences of the squared masses of neutrinos, $\Delta m^2_{ij} = |m^2_i - m^2_j|$, and can therefore not determine the absolute mass values. This absolute mass scale can be deduced from two types of experiments: the search for neutrinoless double β decay, a process that is forbidden in the standard model, and direct kinematic neutrino mass experiments. Both approaches are measuring different parameters and are complementary to each other.

a. Direct searches

Experiments investigating the kinematics of weak decays by measuring the charged decay products to determine absolute neutrino masses have been performed for all three neutrino flavors. The measurement of pion decays into muons and ν_μ at PSI and the investigation of τ-decays into five pions and ν_τ at LEP have yielded the upper limits $m(\nu_\mu) < 190$ keV/c^2 (90% C.L.) (Eidelman *et al.*, 2004) and $m(\nu_\tau) < 18.2$ MeV/c^2 (95% C.L.) (Barate *et al.*, 1998). Experiments investigating the mass of the electron neutrino by analyzing β decays with emission of electrons or positrons have reached a sensitivity in the eV/c^2 mass range. The most sensitive direct searches for the mass of the electron neutrino are based on the investigation of the electron spectrum of tritium β decay

$$^3\mathrm{H} \rightarrow ^3\mathrm{He}^+ + e^- + \overline{\nu}_e \,. \tag{116}$$

A non-zero neutrino mass would slightly change the shape of the β electron energy spectrum at the upper end. However, the interesting part of the β spectrum is only one part in a billion! A long series of experiments with tritium were carried out over the last 20 years. During this period the error bar on m_ν^2 has decreased by almost two orders of magnitude (Fig. 32).

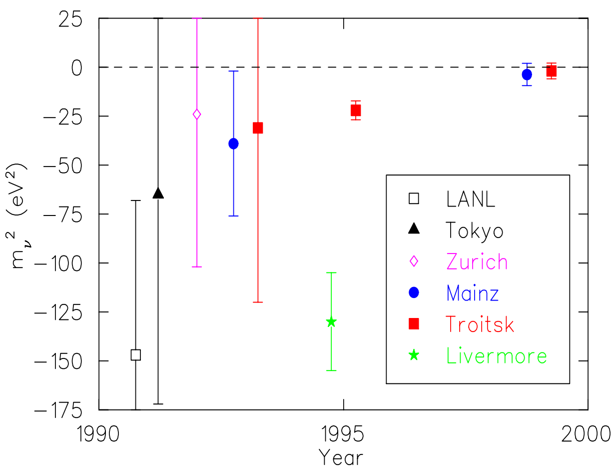

FIG. 32 Results of measurements of $m_{\overline{\nu}_e}^2$ from tritium β decay experiments since 1990. From McKeown and Vogel, 2004.

The problem of negative values for m_ν^2 of the early 1990's (Eidelman *et al.*, 2004) (Fig. 32) has disappeared due to a better understanding of systematics and improvements in the experimental set-ups. The highest sensitivity was reached in experiments at Troitsk and Mainz which used a new type of spectrometers (Lobashev *et al.*, 1999; Weinheimer *et al.*, 1999), so-called MAC-E-Filters for Magnetic Adiabatic Collimation followed by an Electrostatic Filter (Fig. 33). This type of spectrometer combines high luminosity and low background with a high energy resolution. The β electrons from the tritium source placed in the first of a series of superconducting solenoids are guided in a cyclotron motion around the magnetic field lines into the forward hemisphere, resulting in a solid angle acceptance of nearly 2π. Due to the very slow decrease of the magnetic field, by nearly four orders of magnitude, between the first solenoid and the center of the spectrometer, most of the electrons cyclotron energy is transformed into longitudinal motion. The isotropic distribution of the β electrons at the source is thus transformed into a broad beam of electrons flying almost parallel to the magnetic field lines. This parallel electron beam runs against an electrostatic potential created by a set of cylindrical electrodes. Electrons with sufficient energy to pass the electrostatic barrier are re-accelerated and focused onto the detector. All other electrons are reflected. The spectrometer thus acts as an integrating high-energy pass filter, the energy resolution of which is only determined by the ratio between the minimum and the maximum magnetic field in the spectrometer: $\Delta E/E = B_{min}/B_{max}$. By scanning the electrostatic retarding potential the β spectrum can be measured in an integrating mode.

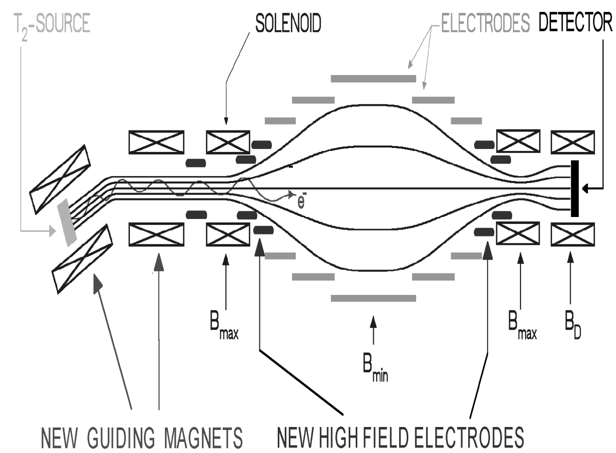

FIG. 33 Schematic drawing of the MAC-E filter used at Mainz for tritium β spectroscopy. From Bonn *et al.* (1999).

For the Troitsk experiment (Lobashev, 2003) the fit of the β spectrum yielded the limit $m_\nu c^2 \leq 2.05$ eV (95% C.L.), whereas the Mainz experiment (Kraus *et al.*, 2003, 2005) obtained $m_\nu c^2 \leq 2.3$ eV (95% C.L.). Both experiments have reached their intrinsic sensitivity limit. A new project, called KATRIN (Osipowicz *et al.*, 2001; Weinheimer, 2002), was recently started at the Forschungszentrum Karlsruhe with the aim of improving the sensitivity to about $m(\nu_e) = 0.35 eV/c^2$ (90% C.L.) assuming three years of measuring time. The main components of this system comprise two tritium sources, two electrostatic MAC-E filter electron spectrometers, and a segmented solid state detector. The overall length of the set-up is about 70 m and the energy resolution is 1 eV.

b. Neutrinoless double β decay

An alternative and very sensitive means to search for non-zero neutrino masses is neutrinoless double β decay ($0\nu\beta\beta$). Physically this means that two β decays occur at the same moment in the same nucleus. This is only observable if the ground state of the β decay daughter of a nucleus has a higher energy than the parent state, such that the parent nucleus must immediately decay to its grand-daughter isotope. The normal double β decay with emission of two electron (anti)neutrinos ($2\nu\beta\beta$) was observed more than 15 years ago (Elliott *et al.*, 1987). This is, however, a process allowed by the standard model, albeit with an extremely low probability. For neutrinoless double β decay to occur the neutrino emitted by one β decaying nucleon inside the nucleus ($n \rightarrow p + e^- + \bar{\nu}_e$) has to be absorbed by the second nucleon undergoing inverse

β decay $\nu_e + n \to p + e^-$. For this to be possible, the neutrino has to have a mass and to be its own antiparticle, that is it has to be a Majorana particle. The process of $0\nu\beta\beta$ violates lepton number.

The search for neutrinoless double beta decay gives new information on the nature of the neutrino (Bahcall *et al.*, 2004). It is the only feasible experimental technique that could establish whether the neutrino is a Majorana particle. If this is indeed the case, these experiments are also sensitive to the mass of the neutrino. Current mass limits from neutrinoless double beta decay are about one order of magnitude more stringent than limits from direct measurements and proposed or suggested experiments will further improve on this (Bahcall *et al.*, 2004). It is to be noted though that neutrinoless double β decay is sensitive to an effective neutrino mass $m_{ee}(\nu)$, which is a coherent sum of all neutrino mass states ν_i contributing to the electron neutrino ν_e according to their mixing described by the neutrino mixing matrix elements U_{ei}, and to their Majorana phases $e^{i\phi_i}$:

$$m_{ee}(\nu) = \left|\sum e^{i\phi_i} U_{ei}^2 m(\nu_i)\right| \tag{117}$$

As the Majorana phases $e^{i\phi_i}$ are unknown and the mixing matrix elements U_{ei} are in general complex, cancellations can occur and $m_{ee}(\nu)$ can become zero or very small even when the mass values $m(\nu_i)$ are non-zero.

No clear indication for neutrinoless double β decay has been obtained so far, although one experiment has reported a possible indication for this decay mode in ^{76}Ge (H. V. Klapdor-Kleingrothaus and Krivosheina, 2001) (see also Aalseth *et al.*, 2002). Recent reviews of this field can be found in Elliot and Vogel (2002); Zdesenko (2002).

F. Tests of CVC and searches for second class currents

The presently best tested consequence of CVC (Sec. II.G) is the requirement that $g_V(q^2 = 0)$ should be constant irrespective of the nucleus considered. Many careful measurements of decay parameters in superallowed $0^+ \to 0^+$ transitions between $T = 1$ states (IV.A.1) have confirmed the CVC hypothesis at the 3×10^{-4} precision level (Hardy and Towner, 2005b). However, tests of the so-called strong form of CVC, relating the weak magnetism form factor uniquely to the corresponding electromagnetic form factor (obtained from the transition rate for the analogous γ decay) are still far from reaching a similar precision. Experimental tests comprise *e.g.* β spectrum shape measurements, measurements of correlations in β decay as well as $\beta - \alpha$ and $\beta - \gamma$ correlation measurements. Reviews of this work can be found in Grenacs (1985); Towner and Hardy (1995). Whereas the CVC hypothesis was confirmed only to an accuracy of $\pm25\%$ in $\beta-\alpha$ and $\beta-\gamma$ correlation measurements, it was confirmed to an accuracy of about 5% in a measurement of the ^{20}F β spectrum shape (Van Elmbt *et al.*, 1987) and in β correlation measurements (Towner and Hardy, 1995).

It is to be noted that in various β correlation experiments the interference between the weak magnetism form factor f_M and the dominant axial form factor g_A, which introduces a deviation from the behavior of the correlation as determined by the g_A form factor alone, appears always in conjunction with an interference term arising from an eventual second class contribution from the induced tensor form factor f_T (Sec. II.G). Correlation experiments therefore test CVC only if one assumes the absence of second class currents. Conversely, experiments designed to observe second class currents have to rely on the CVC predicted value for f_M or on its direct measurement. In correlation experiments on the $\mu^- +^{12} C \to^{12} B + \nu_\mu$ muon capture transition, the prediction of CVC was verified with a precision of about 6% (Grenacs, 1985; Possoz *et al.*, 1977).

Originally, a very sensitive method to search for second class currents seemed to be the comparison of ft-values in mirror transitions which, in the impulse approximation, can be written as (Towner and Hardy, 1995)

$$\frac{ft^+}{ft^-} \propto 1 - \frac{4}{3}\frac{W_0^+ + W_0^-}{2M}\frac{g_T}{g_A} + \delta_{nucl} \tag{118}$$

with W_0^+ and W_0^- the respective endpoint energies and δ_{nucl} a nuclear structure correction that arises from the fact that the wave functions of the two mirror nuclei are not exact isospin eigenstates. However, the average reliability of the calculated values for δ_{nucl} hamper the extraction of any information on possible second class currents, even at the present level of many-body techniques (Smirnova and Volpe, 2003).

An overall analysis (Wilkinson, 2000) of relevant experimental data in the β decay of complex nuclei has yielded a limit on the second class tensor coupling constant of $|f_T/f_M| < 0.1$ (90% C.L.). The most precise results in this respect were obtained in recent precision measurements of the β angular distributions from the aligned mirror pair nuclei ^{12}B and ^{12}N (Minamisono *et al.*, 2003, 1998). This conclusion is supported by evidence from particle studies although there the limits obtained are less stringent (Wilkinson, 2000).

An alternative approach to test CVC and search for second class currents might be precision correlation measurements in neutron decay. As pointed out by Gardner and Zhang (2001), if both the β asymmetry parameter A and the $\beta-\nu$ correlation a could be determined with a precision of 1% or better, this would permit to test the CVC hypothesis and to search independently for second-class currents.

Finally, the scalar form factor was extracted with high precision from the $\mathcal{F}$t value of the superallowed $0^+ \to 0^+$ Fermi transitions, yielding f_S/g_V = -0.00005(130) (Hardy and Towner, 2005b). This form factor should vanish both because of CVC and because it is a second class term.

V. SUMMARY AND CONCLUSION

The current experimental status of the weak interaction in nuclear and neutron β-decay and their potential to search for physics beyond the standard model were discussed. A description of the different formalisms that are used in the literature was given as well as approximate expressions for a number of correlation coefficients. In addition, overall fits of selected data have provided new values and limits for the coupling constants that describe β-decay processes.

Experiments in nuclear β decay have significantly contributed in the past to the determination of basic aspects of the weak interaction. They continue to be a powerful tool to test the underlying symmetries, to determine the structure in more detail and to search for physics beyond the standard model.

Progress in the development of a number of new and advanced experimental techniques, often combined with improved isotope yields, resulted in a series of new precision experiments in nuclear β-decay. These provided important new tests of parity violation and time reversal invariance, new constraints on scalar and tensor contributions, new experimental as well as theoretical results related to the V_{ud} element of the CKM quark mixing matrix, and more stringent direct limits on the neutrino mass.

The development of more intense cold as well as ultracold neutron beams and of improved techniques for neutron polarization, polarimetry and detection led to a significant increase in precision for lifetime measurements and for different correlations in neutron beta decay. Recent correlation experiments have mainly concentrated on improving the determination of the ratio between the axial-vector and the vector form factors, g_A/g_V, for an alternative determination of V_{ud} in order to test the unitarity of the CKM matrix. Stringent P-violation tests and tests of T-invariance were carried out as well.

An important problem during the last decade has been the possible violation of unitarity of the CKM matrix. The value of V_{ud} deduced from the $\mathcal{F}$t-values of superallowed pure Fermi transitions has resulted for a long time in a 2 to 2.5σ deviation from unitarity when combined with the adopted value for the V_{us} matrix element. Nevertheless, the $\mathcal{F}$t-values are consistent at the 3×10^{-4} level confirming the CVC hypothesis. A similar deviation from unitarity was reported in neutron decay, where nuclear structure effects are absent. The result combines the neutron lifetime with the β-asymmetry parameter. This has triggered new determinations of V_{us} in kaon decay as well as a new analysis of existing hyperon beta decay data. All results obtained are consistent, leading to a new value for V_{us} which resolves the long standing unitarity problem. Additional experiments to confirm this new value are ongoing and planned while the form factor $f_+(0)$, which takes into account $SU(3)$ symmetry breaking, is addressed again. Assuming the observed shift in the value of V_{us} is genuine, the unitarity condition is validated for the first row of the CKM matrix and, in addition, the nuclear corrections are put on a solid basis. The very precise average $\mathcal{F}$t-value for the superallowed transitions can now be used to test the understanding of isospin effects in nuclei at an unprecedented level of precision and to carry out detailed studies of the *pn*-interaction near the $N = Z$ line. In turn, the control of nuclear structure effects will permit further tests of the symmetries of the standard model and new searches for physics beyond. Accurate determinations of $\mathcal{F}t$-values for superallowed transitions should therefore be pursued whenever possible. Such determinations require the measurements of the half-life, the corresponding branching and the Q_{EC}-value of the transitions. Mass measurements at the level of 10^{-8} are required to determine these Q_{EC}-values.

New measurements of the neutron lifetime and of the β-asymmetry parameter led to a significant improvement in the determination of the fundamental ratio g_A/g_V. With currently ongoing developments further progress can be expected and it is important that this type of measurements be continued.

Significant progress was also made over the past decade in the search for possible scalar and tensor contributions to the weak interaction. New measurements of different correlations between the spins and momenta of the particles involved in β-decay resulted in improved limits on the couplings and masses of bosons which could generate phenomenological scalar and tensor interactions. Under identical assumptions these indirect limits are often tighter than those obtained by direct searches in collider experiments. Important contributions in the search for scalar currents were provided by the β-ν correlation experiments with ^{32}Ar and ^{38m}K. In the search for tensor currents the contribution of the polarization-asymmetry parameter measurement with ^{107}In is important.

A remarkable development in the field was the introduction of atom and ion traps. These tools have enabled new types of β-ν correlation and β-asymmetry measurements, free of scattering effects and with undisturbed nuclear recoils. Recently, first results from an experiment with ^{38m}K became available, while several other experiments are currently ongoing. Using different experimental methods these $\beta - \nu$ correlation measurements reach the 0.5% precision level. Future experiments could consider to improve this to the 0.1% level. This requires the production of clean and high intensity beams, a detailed understanding of systematic effects and the eventual inclusion of recoil order effects in the data analysis.

New experimental methods which do not use traps are also being developed. These new approaches avoid or at least significantly reduce a number of systematic effects. The new experiments will focus on relative measurements of the β asymmetry parameter, on β asymmetry measurements in a 17 T external magnetic field with polarized nuclei, and on the determination of the β-ν correlation in neutron decay with a retardation spectrometer. A precision of 0.5% to 1% is anticipated.

In the last decade significant progress was also made to test the discrete symmetries of parity and time reversal. The first measurements of the polarization-asymmetry correlation, carried out with ^{107}In and with ^{12}N, yielded the most precise tests of parity violation in nuclear β decay to date. A similar precision was obtained in a measurement of the neutrino asymmetry parameter B in neutron decay. There is strong interest in more precise tests of parity violation in nuclear β decays as these provide stringent constraints on several new extensions of the standard model. Any measurement reaching the level of $500\,\mathrm{GeV/c^2}$ for a possible W boson with right-handed couplings would be very valuable. New techniques should be developed to improve both the yields of the isotopes of interest for such measurements as well as the nuclear polarization.

Important progress in the search for deviations from maximal parity violation can be expected from new measurements of the neutron lifetime, and the β asymmetry as well as the neutrino asymmetry in neutron decay. This is due to recent improvements in the techniques to polarize neutrons and to accurately determine this polarization, and to the development of techniques to keep the neutrons in the measurement volume for a time of the order of their lifetime.

From the observed matter-antimatter asymmetry in the Universe it appears that there should be a new mechanism of time reversal violation in addition to the observed CP-violation that is incorporated in the standard model. New T-violation searches should therefore be pursued vigorously. For the triple correlations there are several orders of magnitude between the current experimental level of sensitivity and the manifestation of a standard model CP-violating effect and there is therefore a wide window available to search for new T-violating mechanisms. Any system is good for such measurements, provided the final state interactions are well under control.

The determination of the R triple correlation in the decay of ^{8}Li has yielded very stringent limits on the presence of T-violating tensor couplings. An ongoing experiment to measure for the first time the R correlation in neutron decay will search for a T-violating scalar component. Two new measurements of the D triple correlation in neutron decay provided new tests of time reversal invariance in the vector and axial-vector parts of the weak interaction. The present results will further be improved in the second phase of both experiments which will potentially reach the 10^{-4} sensitivity level.

Tests for the presence of second class currents, such as in the $A = 12$ system, should be continued and improved. In addition, better tests of the strong CVC, which was so far tested at the 5% level, should be pursued too.

Finally, the efforts to directly determine the electron neutrino mass from a precision measurement of the tritium β spectrum shape near the endpoint have been pursued in recent years by two very precise experiments with retardation spectrometers. Both experiments have now reached their limits of sensitivity and have yielded the most stringent direct upper limits on the mass of the electron neutrino. Based on the experience gained with these set-ups a new facility is now being developed which will be sensitive to a neutrino mass at the 0.3 eV level.

In conclusion, the past two decades have witnessed significant progress in the study of fundamental properties of the weak interaction in both nuclear and neutron β-decay. Many efforts to further improve the sensitivity for this type of experiments are either ongoing or planned. In the years to come, experiments at low energy will thus continue to contribute to the study of weak interaction properties, providing information that is complementary to experiments in muon decay, at colliders or in underground neutrino laboratories.

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APPENDIX A: METRIC AND CONVENTIONS

The analysis of the status of the V-A theory presented in Sec. III and the discussion of the experimental tests in Sec. IV refer to the experimental correlation coefficients which are expressed in terms of the couplings C_i and C_i', defined in Eq. (7). This equation is quoted from Jackson *et al.* (1957a) so that we adopted here their convention for the γ matrices.

Eqs. (10-12) are adapted from Herczeg (2001) and Eqs. (40-43) are adapted from Herczeg (1995a) who uses a representation of the γ matrices –the Bjorken and Drell (1963) convention– which differs from the one used by Jackson *et al.* (1957a). In particular, the signs of γ_5, which enters the projection operators, are opposite in the two representations. All the signs of γ_5 in the equations quoted from Herczeg (1995a, 2001) have hence been changed. We refer the interested reader to the original works for further details.

APPENDIX B: CORRELATION COEFFICIENTS

We list here the expressions of the correlation coefficients calculated by Jackson *et al.* (1957b) for allowed transitions. They contain the model- and nucleus-independent Coulomb corrections of order αZ. Numerical calculations (Vogel and Werner, 1983) show that the approximation used to get to these corrections are accurate at the 10% level. When higher precisions are needed the effect of higher order effects like the induced weak currents, forbidden matrix elements, radiative corrections, the finite size of the nucleus, the electronic environments, etc., should be considered.

In the expressions below, the following notation is adopted: M_F and M_{GT} are the Fermi and Gamow-Teller matrix elements respectively; J and J' are the spins of the initial and final nuclear states; the upper (lower) sign refers to β^- (β^+)-decay.

In addition,

$$\lambda_{J'J} = \begin{cases} 1 & J \to J' = J-1 \\ \dfrac{1}{J+1} & J \to J' = J \\ -\dfrac{J}{J+1} & J \to J' = J+1 \end{cases} \tag{B1}$$

Z is the atomic number of the daughter nucleus, α is the fine structure constant and $\gamma = \sqrt{(1-\alpha^2 Z^2)}$.

$$\begin{aligned} \xi &= |M_F|^2 \left(|C_S|^2 + |C_V|^2 + |C'_S|^2 + |C'_V|^2\right) \\ &\quad + |M_{GT}|^2 \left(|C_T|^2 + |C_A|^2 + |C'_T|^2 + |C'_A|^2\right) \end{aligned} \tag{B2}$$

$$\begin{aligned} a\xi &= |M_F|^2 \Big[-|C_S|^2 + |C_V|^2 - |C'_S|^2 + |C'_V|^2 \\ &\quad \mp 2\frac{\alpha Z m}{p_e} Im\,(C_S C_V^* + C'_S C_V'^*)\Big] \\ &\quad + \frac{|M_{GT}|^2}{3}\Big[|C_T|^2 - |C_A|^2 + |C'_T|^2 - |C'_A|^2 \\ &\quad \pm 2\frac{\alpha Z m}{p_e} Im\,(C_T C_A^* + C'_T C_A'^*)\Big] \end{aligned} \tag{B3}$$

$$\begin{aligned} b\xi &= \pm 2\gamma Re\Big[|M_F|^2 \,(C_S C_V^* + C'_S C_V'^*) \\ &\quad + |M_{GT}|^2 \,(C_T C_A^* + C'_T C_A'^*)\Big] \end{aligned} \tag{B4}$$

$$\begin{aligned} A\xi &= |M_{GT}|^2 \lambda_{J'J}\Big[\pm 2Re\,(C_T C_T'^* - C_A C_A'^*) \\ &\quad + 2\frac{\alpha Z m}{p_e} Im\,(C_T C_A'^* + C'_T C_A^*)\Big] \\ &\quad + \delta_{J'J} M_F M_{GT}\sqrt{\frac{J}{J+1}} \\ &\quad \times \Big[2Re\,(C_S C_T'^* + C'_S C_T^* - C_V C_A'^* - C'_V C_A^*) \\ &\quad \pm 2\frac{\alpha Z m}{p_e} Im\,(C_S C_A'^* + C'_S C_A^* \\ &\quad - C_V C_T'^* - C'_V C_T^*)\Big] \end{aligned} \tag{B5}$$

$$\begin{aligned} B\xi &= 2Re\Big\{|M_{GT}|^2 \lambda_{J'J} \\ &\quad \times \left[\frac{\gamma m}{E_e}\,(C_T C_A'^* + C'_T C_A^*) \pm (C_T C_T'^* + C_A C_A'^*)\right] \\ &\quad - \delta_{J'J} M_F M_{GT}\sqrt{\frac{J}{J+1}} \\ &\quad \times \Big[(C_S C_T'^* + C'_S C_T^* + C_V C_A'^* + C'_V C_A^*) \\ &\quad \pm \frac{\gamma m}{E_e}\,(C_S C_A'^* + C'_S C_A^* \\ &\quad + C_V C_T'^* + C'_V C_T^*\Big)\Big]\Big\} \end{aligned} \tag{B6}$$

$$\begin{aligned} D\xi &= \delta_{J'J} M_F M_{GT}\sqrt{\frac{J}{J+1}} \\ &\quad \Big[2Im\,(C_S C_T^* - C_V C_A^* + C'_S C_T'^* - C'_V C_A'^*) \\ &\quad \mp 2\frac{\alpha Z m}{p_e} Re\,(C_S C_A^* - C_V C_T^* \\ &\quad + C'_S C_A'^* - C'_V C_T'^*)\Big] \end{aligned} \tag{B7}$$

$$\begin{aligned} G\xi &= |M_F|^2 \Big[\pm 2Re\,(C_S C_S'^* - C_V C_V'^*) \\ &\quad + 2\frac{\alpha Z m}{p_e} Im\,(C_S C_V'^* + C'_S C_V^*)\Big] \\ &\quad + |M_{GT}|^2\Big[\pm 2Re\,(C_T C_T'^* - C_A C_A'^*) \\ &\quad + 2\frac{\alpha Z m}{p_e} Im\,(C_T C_A'^* + C'_T C_A^*)\Big] \end{aligned} \tag{B8}$$

$$\begin{aligned} N\xi \;=\; & 2Re\Big\{|M_{GT}|^2\lambda_{J'J}\left[\frac{1}{2}\frac{\gamma m}{E_e}\right. \\ & \times\left(|C_T|^2+|C_A|^2+|C_T'|^2+|C_A'|^2\right) \\ & \left.\pm\left(C_TC_A^*+C_T'C_A'^*\right)\right] \\ & +\delta_{J'J}M_FM_{GT}\sqrt{\frac{J}{J+1}} \\ & \times\Big[\left(C_SC_A^*+C_VC_T^*+C_S'C_A'^*+C_V'C_T'^*\right) \\ & \pm\frac{\gamma m}{E_e}\left(C_SC_T^*+C_VC_A^*\right. \\ & \left.+C_S'C_T'^*+C_V'C_A'^*\right)\Big]\Big\} \end{aligned} \tag{B9}$$

$$\begin{aligned} R\xi \;=\; & |M_{GT}|^2\lambda_{J'J} \\ & \Big[\pm 2Im\left(C_TC_A'^*+C_T'C_A^*\right) \\ & -2\frac{\alpha Zm}{p_e}Re\left(C_TC_T'^*-C_AC_A'^*\right)\Big] \\ & +\delta_{J'J}M_FM_{GT}\sqrt{\frac{J}{J+1}} \\ & \times\Big[2Im\left(C_SC_A'^*+C_S'C_A^*-C_VC_T'^*-C_V'C_T^*\right) \\ & \mp 2\frac{\alpha Zm}{p_e}Re\left(C_SC_T'^*+C_S'C_T^*\right. \\ & \left.-C_VC_A'^*-C_V'C_A^*\right)\Big] \end{aligned} \tag{B10}$$

APPENDIX C: LIMITS AND APPROXIMATIONS

We summarize here several useful limits and approximations of the correlation coefficients presented in Appendix B.

1. Standard model expressions

The standard model assumes only vector and axial-vector interactions with maximal parity violation. In addition it is expected that the effects due to CP (or T) violation are negligible in the light quark sector at the present level of precision. These assumptions result in the conditions $C_V' = C_V, C_A' = C_A, C_S = C_S' = C_T = C_T' = 0$ and $Im(C_i') = Im(C_i) = 0$ for $i = V, A$. Neglecting Coulomb as well as induced recoil effects one then obtains, for the β-neutrino angular correlation coefficient

$$a_{SM} = \frac{1-\rho^2/3}{1+\rho^2} \tag{C1}$$

where ρ is the mixing ratio

$$\rho = \frac{C_AM_{GT}}{C_VM_F}, \tag{C2}$$

for the β-decay asymmetry

$$A_{SM} = \frac{\mp\lambda_{J'J}\rho^2-2\delta_{J'J}\sqrt{\frac{J}{J+1}}\rho}{1+\rho^2}, \tag{C3}$$

for the neutrino decay asymmetry

$$B_{SM} = \frac{\pm\lambda_{J'J}\rho^2-2\delta_{J'J}\sqrt{\frac{J}{J+1}}\rho}{1+\rho^2}, \tag{C4}$$

for the beta-particle longitudinal polarization

$$G_{SM} = \mp 1, \tag{C5}$$

and for the other coefficients

$$b_{SM} = D_{SM} = N_{SM} = R_{SM} = 0. \tag{C6}$$

It is to be noted that the triple correlation coefficients, N and R, are non-zero when Coulomb corrections are included.

2. Approximations for searches of exotic couplings

Approximate expressions of the coefficients given in Appendix B can be obtained for $C_i \ll 1$ and $C_i' \ll 1$, with $i = S, T$, by lowest order developments in terms of these exotic couplings. These expressions show more explicitly the sensitivity of the correlation coefficients to these couplings. In deriving the approximations one assumes maximal parity violation and time reversal invariance for the V- and A-interactions (*i.e.* $C_V' = C_V$, $C_A' = C_A$ with both couplings real), except for the triple correlation D where the possibility for complex couplings has been allowed. In the expressions below the case $\rho = 0$ corresponds to pure Fermi transitions and the limit $\rho \to \infty$ corresponds to Gamow-Teller transitions. The highest sensitivity to terms containing scalar and/or tensor coupling constants is obtained for pure transitions.

Under these assumptions, the Fierz interference term $b' \equiv bm/E_e$ is approximated as

$$\begin{aligned} b' \;\simeq\; & \pm\frac{\gamma m}{E_e}\frac{1}{1+\rho^2}\left[Re\left(\frac{C_S+C_S'}{C_V}\right)\right. \\ & \left.+\rho^2 Re\left(\frac{C_T+C_T'}{C_A}\right)\right] \end{aligned} \tag{C7}$$

The beta-neutrino correlation coefficient can be written as

$$
\begin{aligned}
a \;\simeq\; & a_{SM} \\
& -\frac{1}{\left(1+\rho^2\right)^2}\left[\left(1+\frac{1}{3}\rho^2\right)\frac{|C_S|^2+|C_S'|^2}{C_V^2}\right. \\
& \left.+\frac{1}{3}\rho^2\left(1-\rho^2\right)\frac{|C_T|^2+|C_T'|^2}{C_A^2}\right] \\
& +\frac{\alpha Z m}{p_e}\frac{1}{1+\rho^2}\left[\mp Im\left(\frac{C_S+C_S'}{C_V}\right)\right. \\
& \left.\pm\frac{\rho^2}{3}Im\left(\frac{C_T+C_T'}{C_A}\right)\right]. \qquad \text{(C8)}
\end{aligned}
$$

The beta asymmetry parameter becomes

$$
\begin{aligned}
A \;\simeq\; & A_{SM} \\
& +\frac{\alpha Z m}{p_e}\left[\frac{\lambda_{J'J}\rho^2 \pm \delta_{J'J}\sqrt{\frac{J}{J+1}}\rho}{1+\rho^2}Im\left(\frac{C_T+C_T'}{C_A}\right)\right. \\
& \left.\pm\frac{\delta_{J'J}\sqrt{\frac{J}{J+1}}\rho}{1+\rho^2}Im\left(\frac{C_S+C_S'}{C_V}\right)\right] \qquad \text{(C9)}
\end{aligned}
$$

It is seen that the beta asymmetry parameter cancels for pure Fermi transitions and that it is sensitive to the exotic couplings only via the Coulomb correction term. For a pure Gamow-Teller transition the quantity $\widetilde{A} \equiv A/(1+b')$ becomes

$$
\begin{aligned}
\widetilde{A}_{GT} \;=\; & \frac{A_{GT}}{1+b'} \\
& \simeq \lambda_{J'J}\left[\mp 1+\frac{\alpha Z m}{p_e}Im\left(\frac{C_T+C_T'}{C_A}\right)\right. \\
& \left.+\frac{\gamma m}{E_e}Re\left(\frac{C_T+C_T'}{C_A}\right)\right] \qquad \text{(C10)}
\end{aligned}
$$

where A_{GT} is obtained from Eq. (C9) for $\rho \to \infty$.

The neutrino asymmetry parameter can be approximated as

$$
\begin{aligned}
B \;\simeq\; & B_{SM} \\
& +\frac{1}{1+\rho^2}\left\{\lambda_{J'J}\rho^2\frac{\gamma m}{E_e}Re\left(\frac{C_T+C_T'}{C_A}\right)\right. \\
& \mp\delta_{J'J}\rho\sqrt{\frac{J}{J+1}}\times\frac{\gamma m}{E_e}\left[Re\left(\frac{C_S+C_S'}{C_V}\right)\right. \\
& \left.\left.+Re\left(\frac{C_T^*+C_T^{*\prime}}{C_A}\right)\right]\right\} \qquad \text{(C11)}
\end{aligned}
$$

For a pure Fermi transition $B=0$. It is seen that B and $\widetilde{B} \equiv B/(1+b')$ are insensitive to time reversal violating interactions.

The longitudinal beta polarization coefficient can be written as

$$
\begin{aligned}
G \;\simeq\; & G_{SM}+\frac{1}{1+\rho^2}\frac{\alpha Z m}{p_e}\left[Im\left(\frac{C_S+C_S'}{C_V}\right)\right. \\
& \left.+\rho^2 Im\left(\frac{C_T+C_T'}{C_A}\right)\right] \qquad \text{(C12)}
\end{aligned}
$$

From the comparison of Eq. (C12) and Eq. (C9) it appears that G probes the same couplings as A but with different sensitivities.

The P-odd and T-odd triple correlation coefficient, R, which probes the existence of time reversal violating scalar and/or tensor components can be written as

$$
\begin{aligned}
R \;\simeq\; & \frac{1}{1+\rho^2} \\
& \times\left[\left(\pm\lambda_{J'J}\rho^2+\delta_{J'J}\sqrt{\frac{J}{J+1}}\rho\right)Im\left(\frac{C_T+C_T'}{C_A}\right)\right. \\
& +\delta_{J'J}\sqrt{\frac{J}{J+1}}\rho Im\left(\frac{C_S+C_S'}{C_V}\right) \\
& \left.+\frac{\alpha Z m}{p_e}\left(\lambda_{J'J}\rho^2 \pm 2\delta_{J'J}\sqrt{\frac{J}{J+1}}\rho\right)\right] \qquad \text{(C13)}
\end{aligned}
$$

This correlation cancels for a pure Fermi transition and for a pure Gamow-Teller transition it reduces to

$$
R \simeq \lambda_{J'J}\left[\pm Im\left(\frac{C_T+C_T'}{C_A}\right)+\frac{\alpha Z m}{p_e}\right] \qquad \text{(C14)}
$$

Finally, if we relax the assumption stated above that the V- and A-couplings be both real, allowing for an imaginary phase between them, then the P-even triple correlation coefficient, D, becomes

$$
\begin{aligned}
D \;\simeq\; & \frac{-\rho}{1+\rho^2}\left\{\delta_{J'J}\sqrt{\frac{J}{J+1}}\left[2\frac{Im\left(C_V C_A^*\right)}{C_V C_A^*}\right.\right. \\
& \left.\left.+\frac{\alpha Z m}{p_e}Re\left(\frac{C_S+C_S'}{C_V}-\frac{C_T+C_T'}{C_A^*}\right)\right]\right\} \text{(C15)}
\end{aligned}
$$

The sensitivity of this correlation to the terms between brackets is non-zero only for mixed transitions, *i.e.* $\rho \neq 0$.

3. Right-handed couplings

We restrict here to the simplest case of so-called manifest left-right symmetric models, assuming no CP-violation in the right-handed sector. The correlation coefficients can then be expressed in terms of two parameters: $\delta = (m_1/m_2)^2$ and ζ (see Sec. II.E and Sec. IV.C). In developing the equations that follow, all scalar and tensor couplings were assumed to be zero and time reversal invariance was assumed to hold for the V- and A-interactions.

Assuming the presence of right-handed currents the beta-neutrino correlation coefficient can be written as:

$$a \simeq \frac{\left[1-\frac{1}{3}\rho^2\right]\left[1+(\delta+\zeta)^2\right]-4\delta\zeta}{\left[1+\rho^2\right]\left[1+(\delta+\zeta)^2\right]-4\delta\zeta} \tag{C16}$$

This coefficient looses its sensitivity to right-handed currents in the limit of no mixing, $\zeta \to 0$.

The beta-asymmetry parameter can here be written as

$$A \simeq A_{SM}\left(1+\alpha_{\delta\delta}\delta^2+\alpha_{\delta\zeta}\delta\zeta+\alpha_{\zeta\zeta}\zeta^2\right) \tag{C17}$$

with

$$\alpha_{\delta\delta} = -2\,, \tag{C18}$$

$$\alpha_{\delta\zeta} = \frac{-4\lambda_{J'J}\rho^3 \mp 4\delta_{J'J}\sqrt{\frac{J}{J+1}}\left(1-\rho^2\right)}{\left(\lambda_{J'J}\rho \mp 2\delta_{J'J}\sqrt{\frac{J}{J+1}}\right)\left(1+\rho^2\right)}\,, \tag{C19}$$

and

$$\alpha_{\zeta\zeta} = \frac{-2\lambda_{J'J}\rho}{\lambda_{J'J}\rho \mp 2\delta_{J'J}\sqrt{\frac{J}{J+1}}}\,. \tag{C20}$$

The sensitivity to δ^2 in Eq. (C17), driven by the factor $\alpha_{\delta\delta} = -2$, and is then the same for all types of transitions, whatever their Fermi/Gamow-Teller character. For a pure Gamow-Teller transition one obtains

$$A_{GT} \simeq \mp\lambda_{J'J}\left[1-2\left(\delta+\zeta\right)^2\right]\,. \tag{C21}$$

The ratio between the asymmetry parameters of a mixed and of a pure Gamow-Teller transition then becomes

$$\frac{A^{mix}}{A^{GT}} \simeq \frac{A^{mix}_{SM}}{\lambda^{GT}_{J'J}}\left[1+\left(4+\alpha_{\delta\zeta}\right)\delta\zeta+\left(2+\alpha_{\zeta\zeta}\right)\zeta^2\right]. \tag{C22}$$

where A^{mix} is given by Eq. (C17). Here again, this ratio looses its sensitivity to right-handed currents in the limit of no mixing, $\zeta \to 0$.

The neutrino asymmetry parameter can be written as

$$B \simeq \left[\pm\lambda_{J'J}\rho^2\left(1-y^2\right)-2\delta_{J'J}\sqrt{\frac{J}{J+1}}\rho\left(1-xy\right)\right] \times\left[\left(1+x^2\right)+\rho^2\left(1+y^2\right)\right]^{-1} \tag{C23}$$

where $x=\delta-\zeta$ and $y=\delta+\zeta$.

The longitudinal polarization of beta particles is given by

$$G \simeq \mp\left[1-\frac{2\left(x^2+\rho^2y^2\right)}{1+\rho^2}\right]. \tag{C24}$$

One should stress here that the expressions in Eqs. (C16, C17, C22, C23 and C24) depend all from the mixing ratio ρ which has to be determined from an independent observable. This last observable might also be sensitive to effects due to right-handed currents so that the actual sensitivity of the parameters listed above will change accordingly. Such an effect has been studied more quantitatively by Naviliat-Cuncic *et al.* (1991), for the β-asymmetry parameter in mirror decays.

4. Coefficients in neutron decay

The SM predictions for the correlation coefficients in the decay of the neutron, neglecting Coulomb corrections as well as induced recoil effects, are usually expressed in terms of a single parameter, $\lambda = |\lambda|e^{-i\phi} = g_A/g_V = C_A/C_V$. The assumptions are here identical to those stated in Appendix C.1. In neutron decay we have $J = J' = 1/2$, $M_F = 1$ and $M_{GT} = \sqrt{3}$, such that $\rho = C_AM_{GT}/C_VM_F = \sqrt{3}\lambda$.

The SM expression in this particular case are then

$$a_n = \frac{1-|\lambda|^2}{1+3|\lambda|^2} \tag{C25}$$

$$A_n = -2\frac{|\lambda|^2+Re\lambda}{1+3|\lambda|^2} \tag{C26}$$

$$G_n = -1 \tag{C27}$$

$$B_n = 2\frac{|\lambda|^2-Re\lambda}{1+3|\lambda|^2} \tag{C28}$$

$$D_n = 2\frac{Im\lambda}{1+3|\lambda|^2} \tag{C29}$$

Under the assumptions above $b_n = N_n = R_n = 0$ and $Im\lambda = 0$ such that $D_n = 0$. Again, it should be noted that the triple correlation coefficients, N_n and R_n, are non-zero when Coulomb corrections are included. The parameter λ, or its absolute value, can be determined from a measurement of either a_n, A_n or B_n.

Similarly, in the presence of exotic couplings or in the framework of manifest left-right symmetric models, the expressions of the correlation coefficients in neutron decay can be derived from those given in Appendices B, C.2 and C.3 by choosing the proper sign for the β^--decay and setting $\lambda_{J'J} = 2/3$, $\delta_{J'J} = 1$, $\sqrt{J/J+1} = 1/\sqrt{3}$, and $\rho = \sqrt{3}\lambda$.

Note that because for the neutron $Z = 1$, the factor $\alpha Zm/p_e$ is very small. Even in the middle of the electron energy spectrum its value is only 0.0042, rendering terms proportional to this factor hardly accessible at the present level of precision. On the other hand, the factor $\gamma m/E_e$ equals 0.40 at the end of the electron energy spectrum and 0.57 in the middle of the spectrum giving a sensitivity to the terms proportional to this factor similar to that obtained in nuclear transitions. A more detailed discussion can be found in Glück *et al.* (1995).

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